การปรับตัวของการปฏิบัติการอ่างเก็บน้ำต่อสภาพการเปลี่ยนแปลงภูมิอากาศ กรณีเขื่อนสิริกิติ์ ประเทศไทย

นายวินัย เชาวน์วิวัฒน์

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรดุษฎีบัณฑิต
สาขาวิชาวิศวกรรมแหล่งน้ำ ภาควิชาวิศวกรรมแหล่งน้ำ
คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2556

ADAPTATION OF RESERVOIR OPERATION TO CLIMATE CHANGE CONDITIONS: SIRIKIT DAM, THAILAND

Mr. Winai Chaowiwat

A Dissertation Submitted in Partial Fulfillment of the Requirements
for the Degree of Doctor of Engineering Program in Water Resources Engineering
Department of Water Resources Engineering
Faculty of Engineering
Chulalongkorn University
Academic Year 2013

Thesis Title	ADAPTATION OF RESERVOIR OPERATION TO CLIMATE CHANGE CONDITIONS: SIRIKIT DAM, THAILAND
By	Mr. Winai Chaowiwat
Field of Study	Water Resources Engineering
Thesis Advisor	Associate Professor Dr. Sucharit Koontanakulvong
Thesis Co-Advisor	Professor Dr. Ashim Das Gupta

Accepted by the Faculty of Engineering, Chulalongkorn University in Partial Fulfillment of the Requirements for the Doctoral Degree

....Dean of the Faculty of Engineering

(Professor Dr. Bundhit Eua-arporn)

THESIS COMMITTEE

....Chairman

(Associate Professor Dr. Tuantan Kitpaisalsakul)

....Thesis Advisor

(Associate Professor Dr. Sucharit Koontanakulvong)

....Thesis Co-Advisor

(Professor Dr. Ashim Das Gupta)

....Examiner

(Dr. Piyatida Hoisungwan)

....Examiner

(Dr. Anurak Sriariyawat)

....External Examiner

(Associate Professor Dr. Sutat Weesakul)

วินัย เชาวน์วิวัฒน์ : การปรับตัวของการปฏิบัติการอ่างเก็บน้ำต่อสภาพการเปลี่ยนแปลงภูมิอากาศ กรณีเขื่อนสิริกิติ์ ประเทศไทย. (ADAPTATION OF RESERVOIR OPERATION TO CLIMATE CHANGE CONDITIONS: SIRIKIT DAM, THAILAND) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: รศ. ดร. สุจริต คูณธนกุลวงศ์, อ.ที่ปรึกษาวิทยานิพนธ์ร่วม: ศ. ดร. Ashim Das Gupta, 412 หน้า.

ในช่วงที่ผ่านมา ประเทศไทยได้รับผลกระทบจากการเปลี่ยนแปลงสภาพภูมิอากาศอย่างชัดเจน ซึ่งกระทบต่อสภาพอุทกวิทยาและลักษณะการไหลของลุ่มน้ำอย่างมีนัยสำคัญ โดยเฉพาะอย่างยิ่งรูปแบบของฝนที่ต่างไปจากปัจจุบัน ส่งผลให้สภาพน้ำท่าเปลี่ยนตามไปด้วย ดังปรากฏในปี พ.ศ. 2554 ประเทศไทยได้ประสบกับมหาอุทกภัยในพื้นที่ลุ่มน้ำเจ้าพระยาตอนล่าง เนื่องจากสภาพฝนที่มาเร็วในฤดูฝน และตามมาด้วยพายุฝนที่ตกอย่างหนักในระยะต่อมา สภาพน้ำท่วมได้นำมาซึ่งความสูญเสีย และเสียหายต่อชีวิตและเศรษฐกิจอย่างหนัก ในทางตรงกันข้ามในปี พ.ศ. 2536 และ 2548 ประเทศไทยได้ประสบกับสภาพภัยแล้งอย่างรุนแรงครอบคลุมพื้นที่ส่วนมากของประเทศส่งผลให้เกิดความเสียหายต่อพื้นที่การเกษตรเป็นวงกว้าง การปรับปรุงเกณฑ์การบริหารอ่างเก็บน้ำจึงเป็นทางเลือกหนึ่งที่รัฐบาลได้นำมาใช้จัดการน้ำ เพื่อบรรเทาปัญหาน้ำท่วมในระยะสั้น

จากสาเหตุข้างต้น จึงนำไปสู่การศึกษาการปรับตัวของการปฏิบัติการอ่างเก็บน้ำโดยใช้ข้อมูลระยะยาว เพื่อรองรับต่อสภาพการเปลี่ยนแปลงภูมิอากาศในอนาคต โดยมีวัตถุประสงค์ในครั้งนี้เพื่อเป็นการคาดการณ์สภาพภูมิอากาศในอนาคต การประเมินการเปลี่ยนแปลงของตัวแปรอุทกวิทยา และผลกระทบต่อการบริหารอ่างเก็บน้ำในปัจจุบัน และพัฒนาการปรับตัวของระบบการปฏิบัติการอ่างเก็บน้ำภายใต้การเปลี่ยนแปลงของสภาพภูมิอากาศ โดยปรับปรุงเกณฑ์การปล่อยน้ำด้วยเทคนิคฟัซซีนิวโรให้ตอบสนองต่อความต้องการน้ำ ทั้งด้านชลประทาน อุปโภคบริโภค อุตสาหกรรม และสิ่งแวดล้อม เพื่อให้สามารถลดสภาพขาดแคลนน้ำและสภาพน้ำท่วมของพื้นที่ท้ายน้ำ โดยมีพื้นที่ศึกษาหลัก คือ เขื่อนสิริกิติ์ และลุ่มน้ำน่าน และพื้นที่ลุ่มน้ำประกอบคือลุ่มน้ำเจ้าพระยาใหญ่ จากผลการศึกษา พบว่า การปรับตัวของระบบการปฏิบัติการอ่างเก็บน้ำที่พัฒนาขึ้นสามารถบรรเทาสภาพน้ำขาดแคลน และสภาพน้ำท่วมของพื้นที่ลุ่มน้ำน่านได้อย่างมีประสิทธิภาพ โดยระบบดังกล่าวสามารถปล่อยน้ำได้ตามความต้องการน้ำ ในขณะเดียวกันก็สามารถลดยอดน้ำท่วมได้ดีขึ้นเทียบกับการปล่อยน้ำแบบปกติ และแบบน้ำท่วมที่ดำเนินการอยู่

ภาควิชา	วิศวกรรมแหล่งน้ำ	ลายมือชื่อนิสิต	....
สาขาวิชา	วิศวกรรมแหล่งน้ำ	ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก	....
ปีการศึกษา	2556	ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์ร่วม	....

5171829121 : MAJOR WATER RESOURCES ENGINEERING
KEYWORDS: CLIMATE CHANGE / RESERVOIR OPERATION / ADAPTIVE NEURO FUZZY INFERENCE SYSTEM / RAINFALL-RUNOFF ESTIMATION

WINAI CHAOWIWAT: ADAPTATION OF RESERVOIR OPERATION TO CLIMATE CHANGE CONDITIONS: SIRIKIT DAM, THAILAND. ADVISOR: ASSOC. PROF. DR. SUCHARIT KOONTANAKULVONG, CO-ADVISOR: PROF. DR. ASHIM DAS GUPTA, 412 pp.

In Thailand, climate change has been observed to show the significant impact on the hydrological processes and flow characteristics of main river basins especially in term of rainfall pattern and runoff change in recent years. In year 2011, Thailand had experienced the severe flood in the Lower Chao Phraya River Basin due to the unexpected early started rainfall in the rainy season with high intensity of storm series. The inundation caused by flood has brought the huge loss and damage of lives and economics. On the contrary in year 1993 and 2005, Thailand also experienced the extreme drought in most part of the country; it caused damage widely in agricultural area. Improving the reservoir operation to manage water effectively and cope with future flood event has become an important approach and strategy for short term flood control proposed by the government.

Based on the mentioned reasons, the study on the adaptive reservoir operation to respond to future climate change using long term data was conducted. The objectives are to project the future climate, evaluate the change on hydrological variables, assess impact on the existing reservoir operation and develop the adaptive reservoir operation system under future climate condition. This study improved the reservoir release rules via fuzzy neuro inference techniques (ANFIS) with responding of water demand of irrigation, water supply, industrial and environmental release in order to minimize the water shortage and flood at the downstream. The main study area included Sirikit Dam and Nan River Basin, for the concerned area is Yom, Wang, Ping River Basin and Chao Phraya Irrigation Project. It is found that the developed adaptive reservoir operation system can mitigate the water shortage and flood more effectively, i.e. the proposed reservoir operation system can improve water release to satisfy with water demand and reduce the peak of flood at the downstream compared with the existing general and flood rule curves.

Department: Water Resources Engineering
Field of Study: Water Resources Engineering
Academic Year: 2013

Student's Signature ....
Advisor's Signature ....
Co-Advisor's Signature ....

ACKNOWLEDGEMENTS

Foremost, I would like to express my sincere gratitude to my advisor Assoc. Prof. Sucharit Koontanakulvong for the continuous support of my Ph.D study and research, for his patience, motivation, enthusiasm, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my Ph.D study. My sincere thanks also goes to my co-advisor, Prof. Ashim Das Gupta who has been always guiding me and providing me numerous valuable suggestions and constructive criticisms that have helped me improve my work and research in an international perspective.

Besides my advisor, I would like to thank the rest of my thesis committee: Assoc. Prof. Dr.Tuantan Kitpaisalsakul, Assoc. Prof. Dr. Sutat Weesakul, Dr.Piyatida Hoisungwan and Dr.Anurak Sriaiyawat, for their encouragement, insightful comments, and hard questions.

In the same way, I would like to thank Mr. Chokchai Suthithammajit as well as the researchers and officers from RID, TMD, EGAT and other Thai government agencies and universities, especially Mr. Maitree Foithong, and MRI officers: Dr.Akio Kitoh and Dr. Shoji Kusunoki who had kindly provided me the valuable data and information about the dam operation and so on. Without their generous support and collaboration, I would not have accurate input data to conduct my study to reach the reliable analysis.

I would also like to thank Thailand Research Fund that support the fund for this study and my officemates in Water Resources Management Research Unit Laboratory : for the stimulating discussions, for the sleepless nights we were working together before deadlines, and for all the fun we have had in the past years.

Last but not the least, I would like to thank my family: my mom, Phikul Chaowiwat, for giving birth to me at the first place and supporting me spiritually throughout my life. My wife and my daughter, Wang Yi and Yuyi Chan, they have brightened my life and brought me enormous happiness. Their love and support to my life and work are my inspiration to overcome all the strugglings. I always try my best to make them proud.

CONTENTS

Page

Page

Page

LIST OF FIGURES

Page

Page

Page

Page

Page

LIST OF TABLES

Page

Page

Page

Page

LIST OF ABBREVIATIONS

ANFIS = Adaptive Neuro Fuzzy Inference System
CCCma = The Canadian Centre for Climate Modelling and Analysis, Canada
CCSR = Center for Climate system Research, USA
CSIRO = Commonwealth Scientific and Industrial Research Organisation, Australia
DIW = Department of Industrial Works
DPA = Department of Provincial Administration
DWR = Department of Water Resources
EGAT = Electric Generation Authority of Thailand
GCM = Global Circulation Model
GFDL = The Geophysical Fluid Dynamics Laboratory, USA
LDD = Land Development Department
MSL = mean sea level
MRI = Meteorological Research Institute, Japan
MWA = Metropolitan Waterworks Authority
OAE = Office of Agricultural Economic
PWA = Provincial Waterworks Authority
RID = Royal Irrigation Department
TMD = Thai Meteorological Department

CHAPTER I
INTRODUCTION

Normally, reservoir operation needs to follow the reservoir rule curve, which attempts to store water no less than dead storage at the minimum level. On the other hand, the storage should not be over than the spillway level for the purpose of dam safety. In general, the dam will store water in the wet season for using in the dry season.

The adaptive reservoir operation system in this study was developed to respond to the impact of climate change. The objective of adaptive reservoir operation is to mitigate the water shortage and flood downstream. The adaptive reservoir operation was developed by carrying out change evaluation on climate and hydrological variables, and an impact assessment on the existing reservoir operation and adaptive reservoir operation system development. The system is comprised of the reservoir operation module, the release decision-making module, the water demand decision module and the water network balance module.

1.1 Background and problems

Thailand is located on the southeastern region of the Asia mainland, and area that is facing the impacts from climate change, largely including a rise in sea level, shifts in the climatic zone, and the frequent occurrence of extreme events such as droughts and floods. Recently, the global climate change has affected changes in rainfall, runoff and water demand on both the regional and local scale in Thailand. The flood and drought phenomena tend to be of high severity and frequency (Koontanakulvong, 2011). In Thailand, climate change has been also seen to have a significant impact on the hydrological processes and characteristics of the main river basin, especially in terms of rainfall patterns and runoff changes in recent years (Hunukumbura and Tachikawa, 2012). In 2011, Thailand experienced a severe flood in the Lower Chao Phraya River Basin due to the unexpected early start rainfall in the rainy season, followed by a series of intense storms. The inundation caused by the flood brought about huge losses and damage to people’s lives and to the economy.

The change in climate has also directly affected the hydrological and reservoir operations and water management in the basin scale in Thailand. Most of the reservoirs in Thailand are multipurpose, including flood control, hydropower generation, water supply, navigation, restoration, etc. However, in many cases, the purposes of flood control and hydropower generation are regarded as the most important in the determination of the control strategies for reservoirs. The changing rainfall in the upper watershed has brought changes to the inflow to the reservoirs. The reservoir operations may not be responding to the practical approaches of the past, and it can be expected that the management of reservoir operations in the future will be more difficult due to the risk of natural disasters and the uncertainty of climate change. Thus it is necessary to emphasize that reservoir operation rules should be soundly adapted to global climate change as well as to the economic activities in the river basin.

In recent years, the operation of the main dams in the Chao Phraya River basin were affected by flood events, such as the damages in 2011 and some years of the drought as in 2005, which caused a water supply shortage for the agricultural, domestic and industrial sectors (Chaowiwat and Koontanakulvong, 2010). Hence, in order to cope with flood and drought, the sustainable water operations in the basin should be determined by taking the local climatic fluctuations into consideration. In 2011, the worst flooding worldwide in terms of economic losses happened from 1900 to 2012 in Thailand (EM-DAT, 2012), particularly in the Chao Phraya (CP) River Basin. The geographic location and characteristics of the CP River Basin make it prone to flooding. Disasters are said to be mainly caused by occurrence of several intense rainfalls (Komori et al., 2012). Although the flood disasters were mainly caused by extreme precipitation, other dimensions of flood disasters such as reservoir operations should not be ignored. Around October 2011, for example, several local news sources (Bangkok Post, 2011) pointed out that too much water was being released from the big dams upstream, while flooding was already occurring downstream. The main issue revolves around not reducing the dam storage to a low level because of fears of running out of water for the next dry season. It is important to note that Thailand is an agricultural country which makes it sensitive to droughts. The difficulty in flood risk management in this case arises from conflicts in the storage of water for agricultural purposes for the upcoming dry season.

The dam operations for the allocation of water resources have a propose to meet the spatial and temporal water demand. A decision-making procedure is needed so that reservoir operations can balance the demand and supply for optimal social, economic, and environmental benefits. Water regulations are usually guided by operating rule curves which are defined by rules that indicate a target storage level during different months. The efficiency of a reservoir system is enhanced by improved reservoir operating approaches developed based on a complex optimization technique. However, the development of an adaptive dam operation which bases on the storage condition is a challenging task. A variety of different modeling approaches exist. Traditionally, optimization and simulation techniques are applied to derive operating policies and rules. Thus, it would be valuable to establish an analytic and more systematic approach to dam operations by considering the long-term perspective in order to increase the reservoir’s efficiency for balancing the demands from different users and to meet the requirements for both flood and drought mitigation under the uncertainty of climate and environment change conditions. The above reasons lead to other research issues, for example the adjustment of existing reservoir operations to respond to climate change.

The study components of the adaptation of reservoir operations include the following: 1) present and future GCM climate data preparation for hydrological input variables; 2) inflow and runoff estimation; 3) a water demand decision-making module; 4) ANFIS* reservoir operation decision-making rules; 5) an adaptive reservoir operation model; 6) a water network balance model as illustrated in Figure 1.1. Figure 1.1 shows the input and out variables that are related to the module and models. For example, the inflow and runoff estimation process used rainfall as the input variable to simulate the inflow and lateral flow. The water demand decision-making module used the water demand rate and storage at the end of previous season as the input variables while this module will provides the output variable as the water demand. The ANFIS* reservoir operation decision-making rules used antecedent storage (S_{t-1}), inflow, lateral flow, rainfall downstream, and water demand as the input variables for deciding the release. The adaptive reservoir operation model used inflow, the rainfall over the reservoir area, and release as the input variables to analyze the reservoir water balance. The water network balance model used the release and water demand as the input variables for calculating the water shortage and runoff downstream.

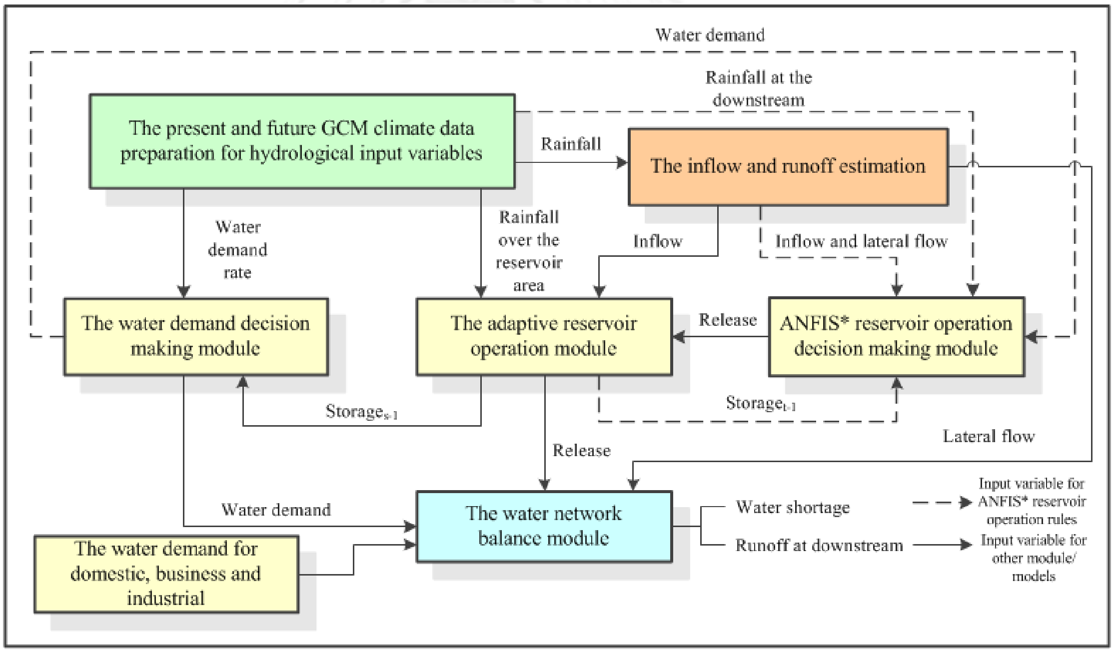


Figure 1.1 The adaptive reservoir operation study components

1.2 Objectives

The specific objectives of the study are:

a) To project the future climate on the Nan River Basin from the bias corrected output of the Global General Circulation Model

b) To evaluate the changes in the hydrological variables
c) To assess the impact of climate change on existing reservoir operations
d) To develop an adaptive reservoir operation system and rules under the climate change conditions

1.3 Research approach and scope

1.3.1 Research approach

To respond to the study objectives, the study was accomplished by adopting the framework as shown in Figure 1-2. This study of the 5 parts included the collecting GCM climate data, the bias correction of GCM rainfall, the change in the hydrological variables, the impact assessment of climate change on the existing reservoir operations and the adaptive reservoir operations as shown in Figure 1-2.

The GCM dataset after bias correction is used for the impact assessment and adaptive reservoir operation system application. The developed adaptive system applied in the impact assessment phase to investigate the advantage of the system to reduce the flood and shortage. In the additional, the adaptive system also applied to the adaption plan to see the effectiveness of the system in the adaptation of climate change.

Regarding the bias correction of GCM rainfall and changes in the hydrological variables, it includes a suitable GCM selection and bias correction method selection. First, a suitable GCM was selected based on its ability to simulate the present climate in a better way when compared with the observed data. The GCM which collected from IPCC distribution center included CCSR model, CSIRO model, ECHAM4/OPYC3 model, GFDL model, HadCM3 model, CCCma3 model and MRI AGCM model. Hence, the MRI GCM SRES scenario A1B, which yields better results and has moderate increasing of emission rate, were used to apply to the bias correction selection method. Second, regarding the bias correction method selection, it was applied to correct the bias of the GCM data. These methods included Gamma-gamma (GG) transformation, the hybrid method, the standard deviation ratio method, and the modified rescaling method.

Furthermore, the evaluation of bias correction methods on precipitation can be compared with the statistical characteristics such as maximum, minimum, mean, and standard deviation.

Regarding the evaluation of the changes in the hydrological variables, they can be separated into the future climate and water demand projection groups and the future runoff estimation group. The future climate and water demand projection groups include rainfall, maximum, minimum, and mean temperature and evapotranspiration. Hence, the evapotranspiration was calculated using the Penman-Monteith equation. Therefore, the evapotranspiration was used to calculate the water demand rate under the GCM climate condition. For the future runoff estimation group, the runoff was simulated using the HEC-HMS rainfall-runoff model, which uses the bias-corrected rainfall as the input variable data. The bias correction of the GCM rainfall and changes in the hydrological variables are presented in Chapter 5.

Regarding the impact assessment of the existing reservoir operations, the reservoir operation model included 4 developing parts: 1) the reservoir operation model (main part); 2) the water demand decision-making module; 3) the water network balance model; and 4) the release rule module. Therefore, the impact on the existing reservoir operation was assessed by simulating the general and flood reservoir operations with present, near, and far future input hydrological variables. Furthermore, the statistic inference of the model results, which included reservoir water balance, spillage, water shortage and runoff at the downstream, were compared. The impact assessment of climate change on the existing reservoir operations is presented in Chapter 6.

Adaptive reservoir operation is a process to improve the effectiveness of existing reservoir operation affected from the climate change. The reservoir operations development included: 1) adaptive neurofuzzy inference system (ANFIS) release rule formulation; 2) ANFIS reservoir operation model development and capability exploration; 3) ANFIS reservoir operation modification (called ANFIS*); 4) ANFIS* reservoir operation simulation with present, near and far future input hydrological variables; and 5) the adaptive effectiveness of ANFIS* reservoir operations was evaluated by comparing the existing and ANFIS* reservoir operations under GCM climate conditions by investigating flood and drought situation compared with present condition. The adaptive reservoir operations under climate change conditions are presented in Chapter 7.

This thesis also presents new components of reservoir operations which added decision-making modules, such as the adaptive reservoir operation rule and water demand decision-making module. The adaptive reservoir operation also provides alternative release rules for reservoir operators. The reservoir can thus be regulated in a practical way by using the release – storage ratio (see details in Chapter 7.7 and Appendix D). Furthermore this reservoir operation model can be used as a guideline to operate the reservoir on a monthly basis.

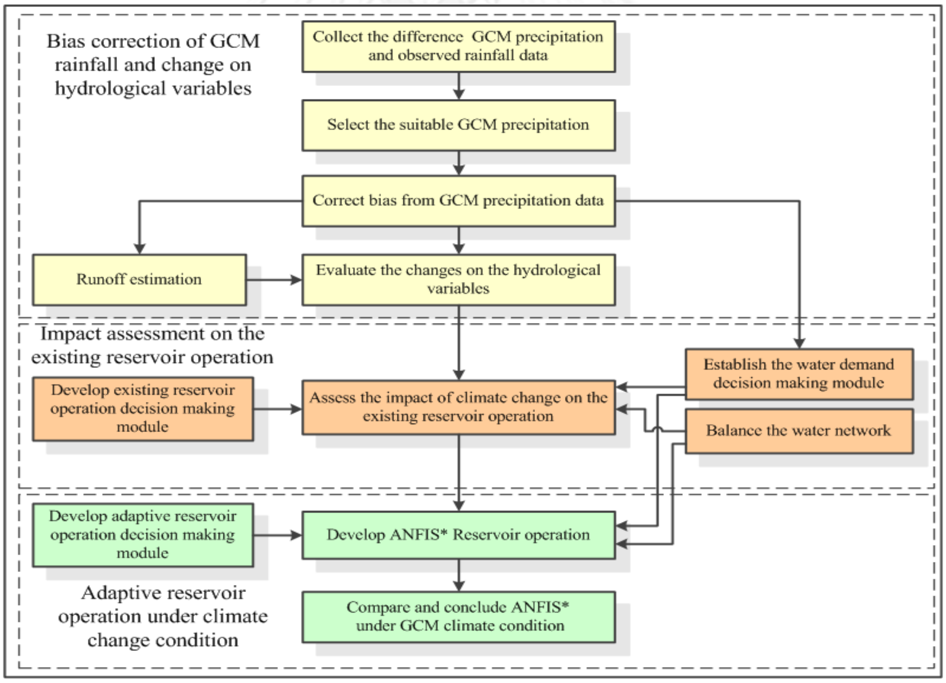


Figure 1.2 Schematic representation of the study framework

1.3.2 Research scope

1.3.2.1 Scope

The scope of this research includes:

1) The bias correction of GCM rainfall and change in the hydrological variables comprises 2 parts: first, the bias correction of GCM rainfall includes GCM selection and a comparative study of the bias correction of GCM rainfall methods. The mean GCM data selection was used to compare the simulating ability of the GCM data, while the comparative study of the bias correction of the GCM rainfall methods evaluated the performance of different bias correction, such as the Gamma-gamma (GG) transformation, hybrid method, standard deviation ratio method, and the modified rescaling method. Second, the change in the hydrological variables was used to evaluate the climate and runoff change under GCM climate conditions. The bias corrected GCM climate data were analyzed from the hybrid bias correction method. Thus, the runoff was estimated by using the HEC-HMS rainfall-runoff model with the parameter estimation method.

2) The impact assessment of climate change on the existing reservoir operations included the general and flood reservoir operation development and assessed the impact under GCM hydrological input variables. The existing reservoir operation development includes: 1) the reservoir operation model (main part), which is based on the reservoir water balance equation; 2) the water demand decision-making module, which used the decision tree classification method; 3) the water network balance model, which is based on the water network balance equation; and 4) the release rule module, which is based on the release–effective storage ratio and the decision tree classification method.

3) The adaptive reservoir operation under climate change condition includes ANFIS reservoir operation development, ANFIS* reservoir operation development and the effectiveness of ANFIS* reservoir operation evaluation. The evaluation of effectiveness of reservoir operations used the hydrological data in 1987 – 2012. The adaptive neurofuzzy inference system (ANFIS) method was adopted to develop the release rules by calibrating

and verifying the rules with the actual reservoir operation. To improve the effectiveness of reservoir operation, the ANFIS reservoir operation model was modified by using the results of the adjusting general release rule as the input variables.

1.3.2.2 Study area

The study area of this thesis is Sirikit Dam and Nan River Basin, and the concerned areas are Ping River Basin which includes Bhumibol Dam, and the Wang and Yom River Basin, which concerned as the lateral flow in the water network balance model. The details of the study and concern area are discussed in Chapter 2.

1.3.2.3 Time period

The time period for this thesis which was based on the GCM data period, included 3 periods: the present period (1979 – 2006), the near future period (2015 – 2039) and the far future period (2075 – 2099).

1.3.2.4 Content

The content of this thesis is composed of 8 chapters, with the details of each chapter as follows:

Chapter I, introduction, includes the background and problems, objectives, research approach and scope, and study procedures and outcome expected.

Chapter II includes the characteristic of the study area such as boundary and location, topography, meteorology and hydrology, land use, irrigation development projects, agriculture, existing water usage, flood problems, and existing water management.

Chapter III is comprised of the literature review and includes GCM selection, bias correction of GCM climate and precipitation, rainfall-runoff estimation, and decision-making analysis for water management and reservoir operations.

Chapter IV discusses theories and procedures, including the procedures of the bias correction of GCM rainfall such as the Gamma-

gamma (GG) transformation, the hybrid method, the SD ratio method and the modified rescaling method, the change evaluation of the hydrological variables, the impact assessment of the existing reservoir operations and adaptive reservoir operation development.

Chapter V is a discussion of the bias correction of GCM and changes in the variables, including an introduction, GCM selection, a comparative study of the bias correction method, trends in climate and rainfall change, trends of water demand changes, trends of runoff changes and a summary of the changes in the hydrological variables.

Chapter VI focuses on the impact assessment of existing reservoir operations, including the impact assessment of the general and flood reservoir operations, the Plaichumphol Irrigation Project, and a summary of the changes in the hydrological variables.

Chapter VII includes a discussion of adaptive reservoir operations, including adaptive reservoir operation development, ANFIS reservoir operation components, ANFIS* reservoir operation processes, and the results and discussion that include the model calibration and verification and the effectiveness of ANFIS* reservoir operation evaluation, proposed reservoir operation rule curves, and a summary of adaptive reservoir operations.

Chapter VIII included the conclusions and recommendations from the study, including a conclusion for each chapter and recommendations for practical water management and future research.

1.4 Study procedures

This study is composed of 3 main components: the bias correction of GCM rainfall and changes in the hydrological variables, the impact on existing reservoir operations, and adaptive reservoir operations. The details of these components are as follow:

1.4.1 The bias correction of GCM rainfall and changes in the hydrological variables

1.4.1.1 The bias correction of GCM rainfall

The following procedures were followed: 1) collect the climate data from meteorological stations and GCM climate data from IPCC Distribution Center; 2) select a suitable GCM data; 3) correct the bias of GCM data from the different bias correction methods such as Gamma-Gamma transformation, hybrid method, standard deviation (SD) method and modified rescale method; 4) test the performance of the bias correcting methods by using the statistical parameters; and 5) summarize the results of the projected and bias corrected climate data for generating a runoff in the next procedure.

1.4.1.2 The changes on hydrological variables

1.4.1.1.2 Change on climate and water demand

The following procedures were followed: 1) collect the observed and GCM data include maximum, minimum and mean temperature, relative humidity and rainfall; 2) apply the hybrid bias correction method to the GCM climate data in the present, near, and far future; 3) estimate the water demand unit by estimating the evapotranspiration using the Penman–Montein method in the Phitsanulok and Chao Phraya Irrigation Projects; 4) evaluate the changes in the climate and water demand by comparing the future period results with present period results.

1.4.1.1.3 Change on runoff (inflow and sideflow)

The following procedures were followed: 1) collect the runoff data from the runoff gauge stations and the related input parameters of rainfall-runoff model; 2) simulate the runoff the present and future runoff by using rainfall-runoff model; and 3) evaluate the changes in the runoff by comparing the future period results with the present period results.

1.4.2 The impact on the existing reservoir operation

The following procedures were followed: 1) collect and enter the input variables into the reservoir operation model; 2) collect the historical cultivated area and basic information for water demand estimation; 3) develop a reservoir operation model based on the reservoir water balance equation; 4) develop a water demand decision-making module; 5) develop a water network balance model and integrate this model with the reservoir operation model; 6) develop release rules as a water release decision module by calculating the release–effective storage ratio for general and flood control operation; 7) apply the general and flood release rules to the reservoir operation model; and 8) assess the impact of climate change on the reservoir water balance, water shortage, spillage, and accumulative runoff downstream under general and flood control dam operations.

1.4.3 Adaptive reservoir operations

The following procedures were followed: 1) formulate adaptive neurofuzzy inference system (ANFIS) release rules by calibrating and verifying the release rule with the actual dam operation; 2) develop an ANFIS resevoir operation model by integrating the ANFIS water release decision making rules, the water demand decision-making module, the reservoir operation model and the water network balance module; 3) explore the capability of ANFIS reservoir operations (see Appendix D.2.4); 4) modify the ANFIS reservoir operation model (call ANFIS*) and calibrate for suitable membership functions by adjusting general dam operations to minimize water deficit and spillage; 5) apply the ANFIS* dam operations (see Appendix D.2.5) by using the GCM hydrological input variables; and 6) Compare and conclude the adaptive effectiveness of ANFIS* dam operations under GCM climate conditions.

1.5 Study outcomes

1) Understand the changes and impacts of climate on the hydrological processes in the Nan River Basin in the present and future.

2) Achieve an adaptive (ANFIS) reservoir operation system by coping water demand decision-making module and reservoir operation model.

3) Achieve adaptive (ANFIS) reservoir operation rules while reducing water shortages and floods.

CHAPTER II

STUDY AREA

2.1 Study area

The boundary of the study area mostly covers the main Nan River Basin. The Sirikit Dam was selected as the case study for the adaptive dam operation. Although the Sirikit Dam supplies some water to the irrigated area in the Nan River Basin as the main area, some water has to be allocated to Chao Phraya Irrigation Project also. As a result, this study considered Bhumibol dam operations conjunctively with the Sirikit Dam operations as the area of concern, as shown in Figure 2.1. The related lateral flows or sideflows from the other main basins are considered as one of the components for the study of the water balance of Chao Phraya River Basin, and the lateral flow is considered at the runoff stations located at the outlet of the basin, as shown in Figure 2.1. Hence, the Great Chao Phraya River Basin includes the Ping River Basin, the Wang River Basin, the Yom River Basin, the Sakaekang River Basin, the Upper Chao Phraya River Basin and Nan River Basin. For the Ping River Basin, the inflow of Bhumibol Dam and the runoff from the Lower Ping River Basin are considered as the input variables. The sideflow of the Ping River Basin was set up at runoff station P.17 at Ban Tha Ngiu as the control point. For the Wang River Basin, the runoff of Wang River Basin was considered as the input variable. The sideflow of Wang River Basin was set up at runoff station W.4A at Ban Wang Man as the control point. For the Yom River Basin, the runoff of the Yom River Basin was considered as the input variable also. The sideflow of the Yom River Basin was set up at runoff station Y.17 at Ban Sam Ngam as the control point. Furthermore the Chao Phraya Irrigation Project was considered for the study of the irrigated water demand of Bhumibol and Sirikit Dam as shown in Figure 2.1. Thus, this study focused on the Nan River Basin as the main study area, so the information about the Nan River Basin was studied in more detail, and the Ping, Wang and Yom River Basin were considered as the area of concern.

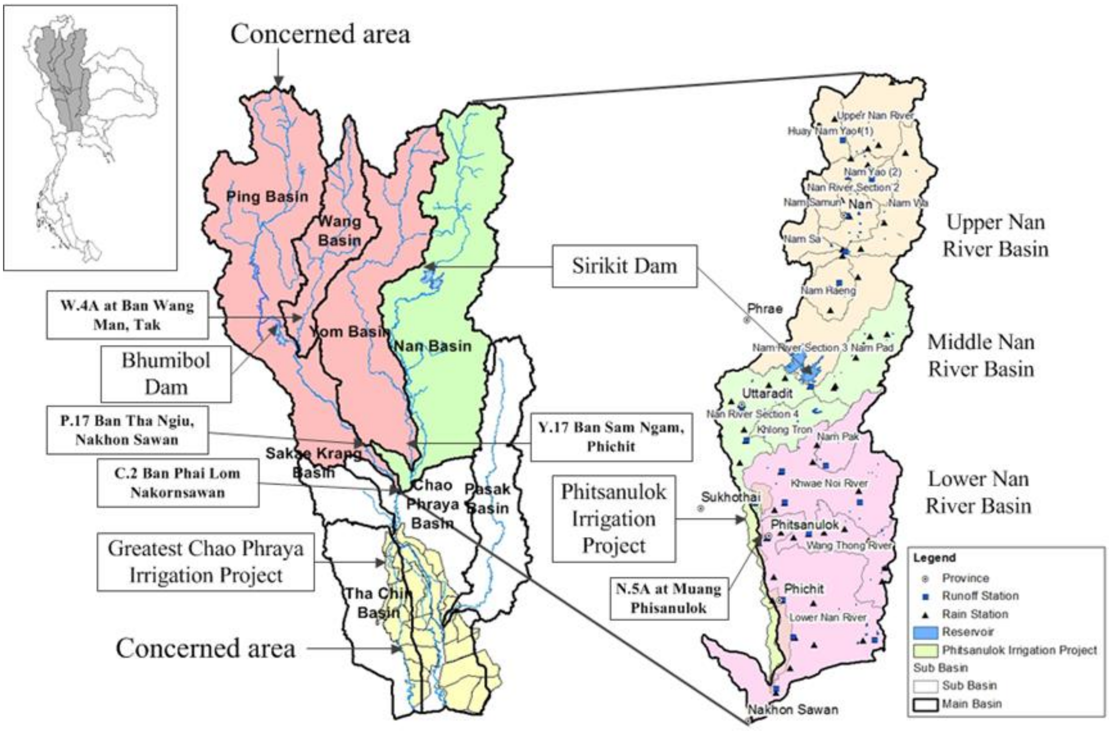


Figure 2.1 Study area

2.2 Topography

The Nan River Basin is located in the northern region of Thailand in a total catchment area of 34,330 square kilometers, and it originates from Kao Luang Prabang mountain, which is on the border line between Thailand and the Lao People's Democratic Republic, situated between Latitude 15° 42’ to Latitude 19° 37’ N and Longitude 99° 51’ to Longitude 101° 21’ E. Its total length is about 770 Km^2. The flow direction is from north to south though Uttaradit, Phitsanulok, Phichit and Nakhon Sawan joins with the Ping River Basin at Pak Nam Pho, Nakhon Sawan province. The Nan River joins the Yom River in Chum Saeng district, Nakhon Sawan Province.

The topography of the Nan River Basin seems as the feather feature, it is narrow and tapering. The topography is high mountain range, the height of the riverside area is about 220 m MSL, and the average slope is about 1:480 in Thung Chang and Cheang Klang Districts. The Nan River flows into the flat plain and valley in Wiang Sa District, Nan Province. There are many streams flow together, such as Nam Wa, Nam Yao and Nam Heang, etc. This area is highland, and the attitude from sea level is about 180 – 220 m MSL and the slope is about 1:3,500. After that the Nan River flows though Wiang Sa District passing the valley to Sirikit Dam, and the slope decreases to 1:5,300 before flowing though the Lower Nan River Basin. The characteristic of the Nan River Basin is that it is a mountainous area in the eastern part and tilts in the western part, which is a wide flat plain. From the lower Naraesuan diversion dam downward toward Nakhon Sawan Province, the average height is about 27 m MSL, and the slope decreases to about 1:13,600 (RID, 2005).

The boundary of the Nan River Basin covers the area of 6 provinces divided into 16 sub-river basins, as shown in Figure 2.1. The Nan River Basin is the main water resource of the central region of Thailand, and Sirikit Dam which is the second greatest dam located in this river basin.

Table 2.1 Sub basin areas in Nan River Basin boundary

Sub basin code	Sub basin name	Area (Sq.Km)	Proportion (%)
0902	Upper Nan River	2,224.77	6.52
0903	Huay Nam Yao (1)	863.54	2.53
0904	Nan River Section 2	1,449.68	4.25
0905	Nam Yao (2)	596.78	1.75
0906	Nam Samun	583.55	1.71
0907	Nam River Section 3	3,376.98	9.89
0908	Nam Sa	753.62	2.21
0909	Nam Wa	2,203.64	6.45
0910	Nam Haeng	1,045.03	3.06
0911	Nan River Section 4	2,759.65	8.08
0912	Nam Pad	2,436.62	7.14
0913	Khlong Tron	1,266.50	3.71
0914	Khwae Noi River	4,483.13	13.13
0915	Nam Pak	968.91	2.84
0916	Wang Thong River	1,999.06	5.86
0917	Lower Nan River	7,128.22	20.88
Total		34,139.68	100

2.3 Meteorology and hydrology

2.3.1 Meteorology

The meteorology in this study was analyzed at the meteorological stations located in the basin area and vicinity, including Tha Wang Pla station, Nan station, Uttaradit station, and Phitsanulok and Nakhon Sawan stations (shown in Figure. 2-2).

The main climate data included temperature 25.2 – 28.2 °C, relative humidity 70.4 – 79.8 % , cloud cover 5.1 – 5.6, wind speed 0.6 – 3.0 knot, pan evaporation 1,244.5 – 2,018.0 mm and Modified Penman reference evapotranspiration 1,588.6 – 1,935.9 mm (as shown in Table 2.2). The monthly mean climate was averaged from the monthly climate data of the meteorological stations in Nan River Basin (shown in Figure 2.3). The monthly mean climate included maximum temperature, minimum temperature, mean temperature, relative humidity, evaporation, dew point, cloud cover and wind velocity.

Table 2.2 Summary of annual mean climate data in Nan River Basin

Climate data	Unit	Annual range	Annual mean
Temperature	°C	25.2 – 28.2	26.8
Relative humidity	%	70.4 – 79.8	74
Wind velocity	Knot	0.6 – 3.0	1.3
Cloud cover	0-10	5.1 – 5.6	5.4
Pan Evaporation	mm/year	1,244 – 2,018.0	1,596.3

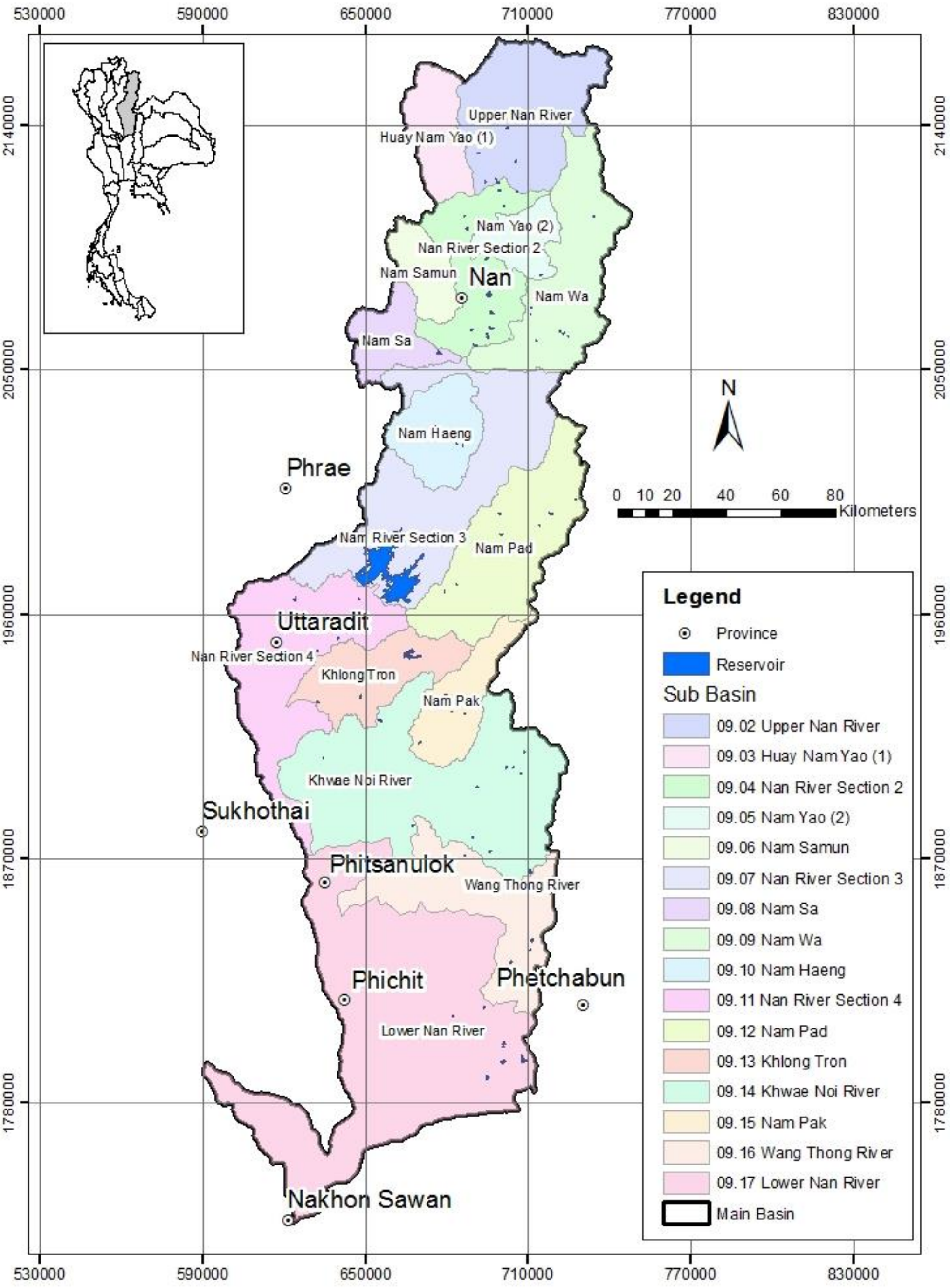
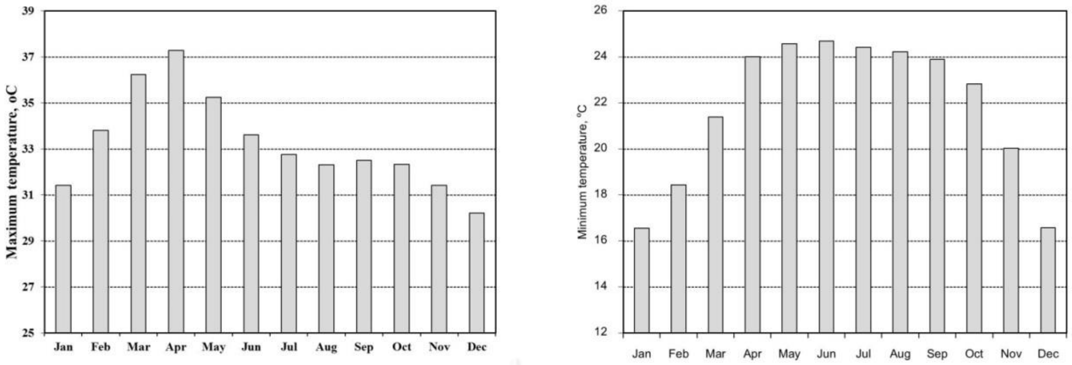
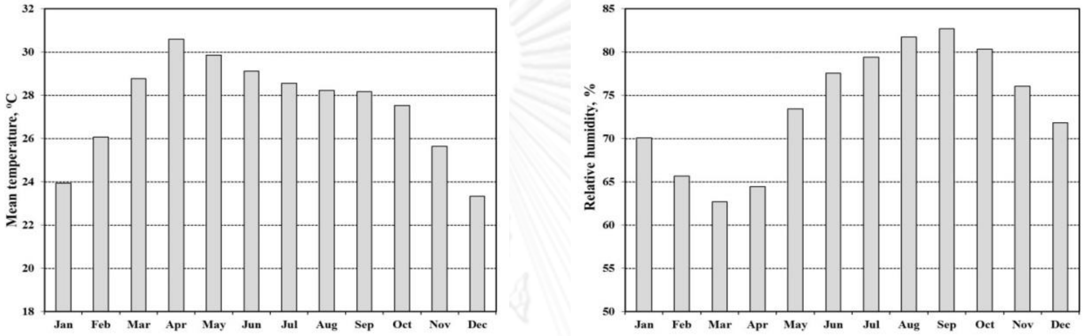


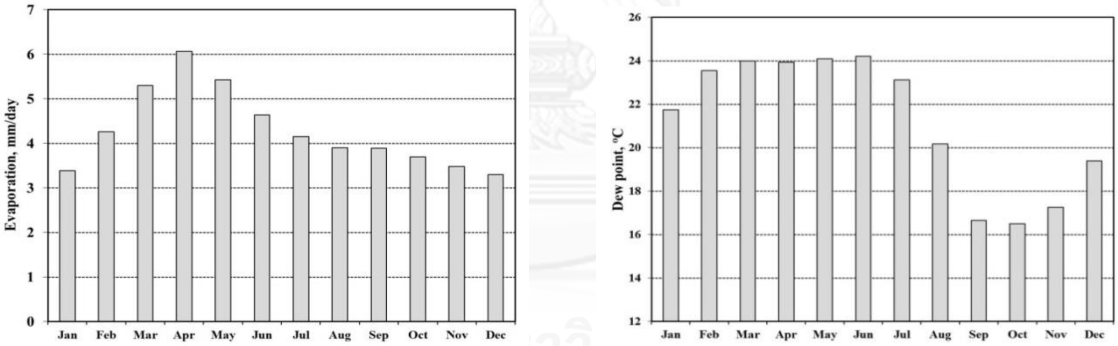
Figure 2.2 The sub basin in the Nan River Basin



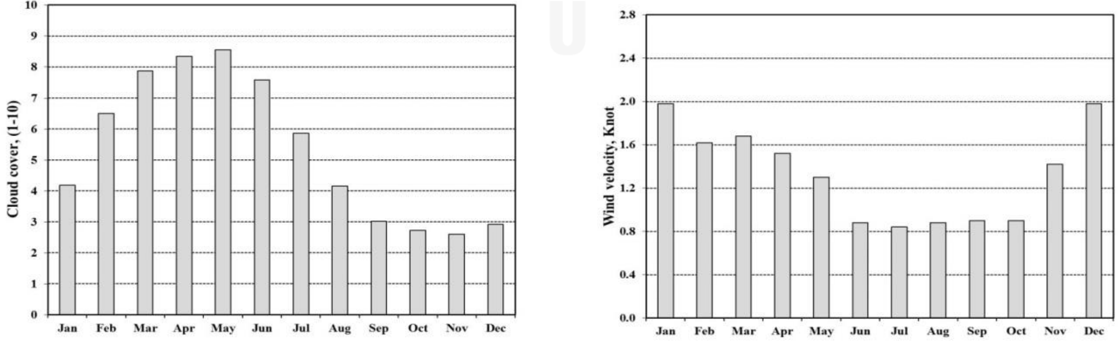
(a) Maximum temperature (b) Minimum temperature



(c) Mean temperature (d) Relative humidity



(e) Evaporation (f) Dew point



(g) Cloud cover (h) Wind velocity

Figure 2.3 Monthly mean climate of Nan River Basin

2.3.2 Rainfall

The rainfall data from 64 rainfall gauge stations were used to analyze the average annual rainfall in the Nan River Basin and its vicinity area and varied between 1,159 – 1,491 mm/year, the maximum average annual rainfall depth was 1,491 mm/year in Huay Nam Yao (1) sub basin. The monthly rainfall of the Nan River sub basin was analyzed by using the theissen polygon averaging method as shown in Table 2.3. The monthly mean rainfall in the Nan River Basin was analyzed and is shown in Figure 2.4. The overall average annual rainfall for the Nan River Basin is 1,267.7 mm/year separated in wet season 1,113.9 mm and dry season 153.8 mm. The distribution of rainfall stations is shown in Figure 2.5, and the details of the rainfall stations are shown in Table A.1. The high intensity of annual rainfall, mostly distributed in the Upper Nan River Basin and Huay Nam Yao(1), has an amount of rainfall over 1,500 mm/year (as shown in Figure 2.5).

Table 2.3 Monthly rainfall in Nan River Basin

Sub basin code	Monthly rainfall, mm/month												Wet	Dry	Annual
	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	(mm)	(mm)	(mm)
0902	92.9	175.4	171.8	267.8	293.4	208.9	88.9	25.4	10.6	4.4	10.8	33.9	1,206.3	178.0	1,384.2
0903	98.5	199.6	197.7	292.3	308.7	215.7	92.7	27.3	9.6	5.8	9.5	34.1	1,306.6	184.7	1,491.4
0904	91.6	179.4	157.8	217.1	269.9	205.2	74.6	22.4	8.6	3.6	10.1	30.7	1,104.0	167.0	1,270.9
0905	83.0	170.7	166.1	230.2	274.5	207.0	81.6	22.8	8.3	3.4	9.4	31.0	1,130.0	157.9	1,287.9
0906	98.6	185.1	150.0	215.0	282.1	203.8	69.6	24.0	9.1	3.6	10.4	31.6	1,105.5	177.3	1,282.8
0907	79.9	186.0	158.3	165.4	217.8	217.0	87.7	19.2	5.7	3.6	10.5	26.0	1,032.2	144.8	1,177.0
0908	91.2	183.9	148.3	180.1	238.2	197.3	68.3	19.2	7.9	3.3	11.5	28.3	1,016.0	161.4	1,177.5
0909	76.5	170.8	165.4	214.9	261.0	215.1	84.3	19.1	5.8	3.0	9.8	27.8	1,111.6	142.0	1,253.6
0910	76.6	179.5	133.9	144.9	192.7	206.8	88.6	18.7	6.0	3.3	10.3	26.2	946.4	141.0	1,087.5
0911	65.8	206.2	176.9	165.4	231.6	236.3	98.1	23.6	5.0	3.6	9.3	21.5	1,114.6	128.8	1,243.5
0912	78.1	182.4	159.8	159.2	207.1	225.6	87.7	15.0	4.0	3.4	9.1	28.1	1,021.8	137.6	1,159.3
0913	71.4	196.3	165.8	160.5	219.2	238.2	103.5	22.3	5.6	4.6	6.6	20.9	1,083.5	131.4	1,214.8
0914	75.1	196.2	195.4	198.0	239.8	249.1	117.1	21.1	4.9	4.3	12.4	33.7	1,195.5	151.5	1,347.0
0915	75.6	195.4	196.1	196.3	245.4	260.6	110.8	21.7	4.2	3.5	10.5	25.9	1,204.6	141.4	1,345.9
0916	87.8	207.0	185.2	176.9	222.2	255.6	124.5	26.2	5.8	5.4	14.5	38.8	1,171.3	178.5	1,349.8
0917	64.2	167.1	163.6	163.2	210.9	248.0	119.8	24.6	3.7	3.9	12.0	29.1	1,072.6	137.5	1,210.1
Total	81.7	186.3	168.3	196.7	244.7	224.4	93.6	22.0	6.6	3.9	10.4	29.2	1,113.9	153.8	1,267.7

Remark : The sub basin code was referred in Table 2-1.

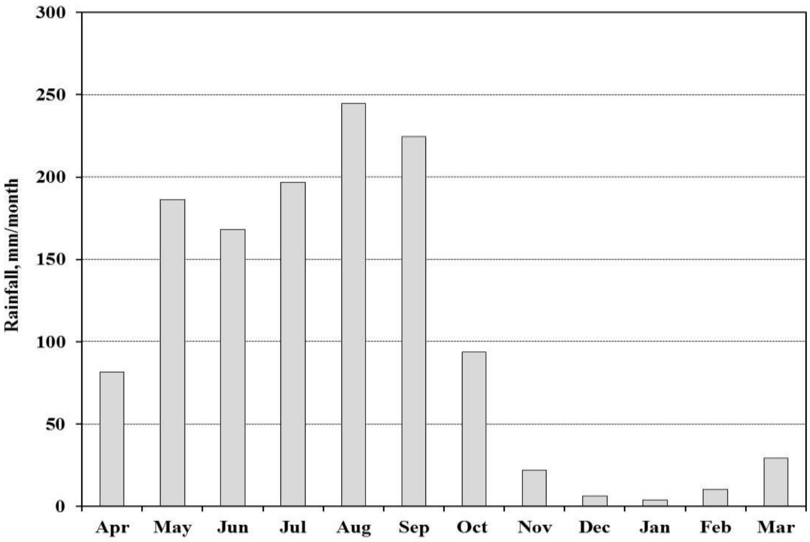
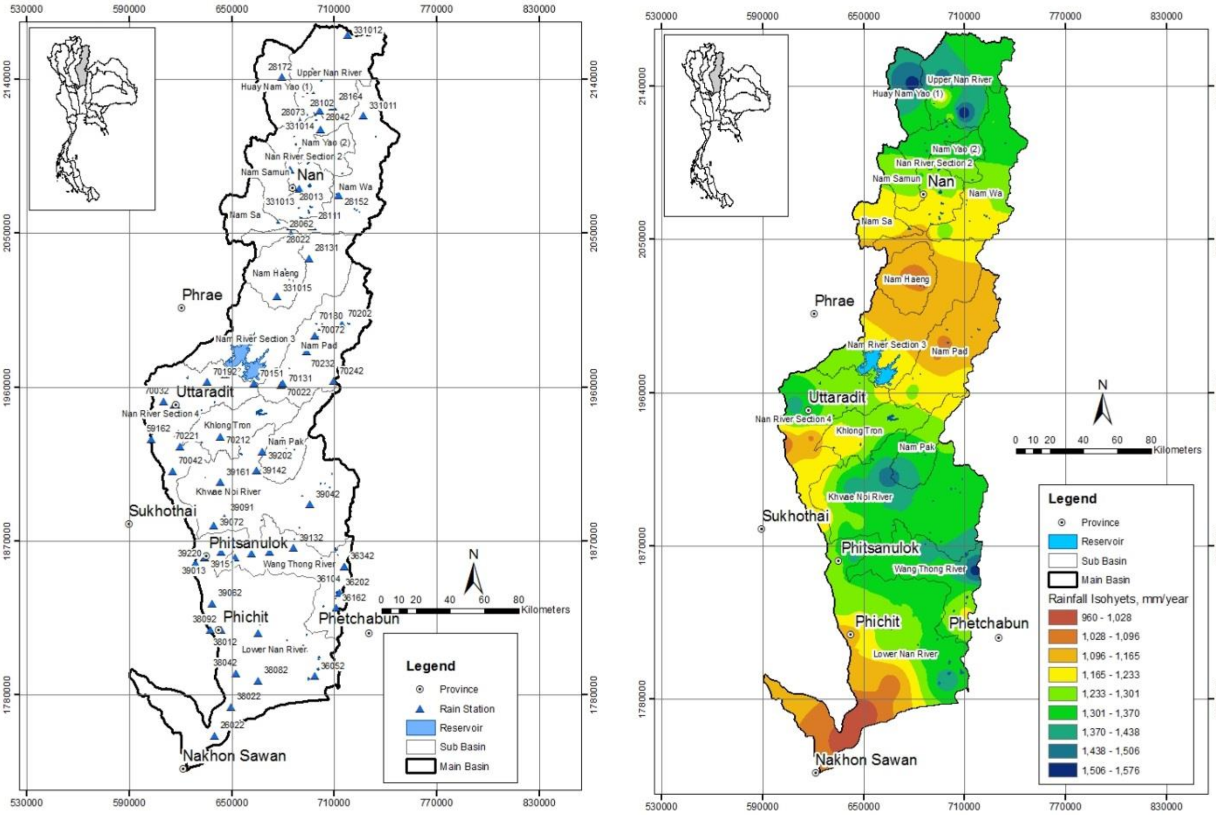


Figure 2.4 Monthly mean rainfall of Nan river basin



(a) Distributed rainfall stations (b) Annual rainfall isohyets

Figure 2.5 Distributed rainfall stations and annual rainfall isohyets in Nan River Basin

2.3.3 Runoff

The runoff data from 27 runoff gauge stations were used to analyze the monthly runoff by using the area proportion method and the location of the runoff gauge stations is shown in Figure 2.6. The mean annual runoff in the Nan river basin is 12,017 MCM/year separate in wet season 9,228 MCM and dry season 2,789 MCM and the average annual specific yield is 11.16 l/sq.km. The monthly runoff was reviewed from the Thailand Research Fund study and the results are shown in Table 2.4 (TRF, 2010). The Pad Sub-River basin has a low figure of 5.01 liter/sq.km, and the Wa Sub-River Basin has the highest figure of 27.26 l/sq.km. The runoff yield was analyzed from the runoff gauge stations and revealed that Huay Nam Yao(1) gives the highest runoff yield according to rainfall intensity (shown in Figure 2.5). The details of the runoff gauge stations are shown in Figure 2.7 and Table A.2.

Table 2.4 Monthly runoff in Nan River Basin (year 1979 – 2008)

Sub basin code	Monthly runoff, Mm^3/month												Wet (Mm^3)	Dry (Mm^3)	Annual (Mm^3)	Specify yield (l/Sec/Km^2)
	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar				
0902	15	46	85	231	463	360	142	67	39	25	15	13	1,328	173	1,501	21.39
0903	4	14	25	68	135	105	41	20	12	7	4	4	388	51	439	16.10
0904	6	16	33	89	175	148	54	24	14	9	6	5	515	63	578	12.65
0905	2	5	10	27	53	45	16	7	4	3	2	2	156	19	175	9.29
0906	2	5	10	26	51	43	16	7	4	3	2	2	151	19	170	9.22
0907	9	34	48	73	140	202	74	18	8	4	2	3	571	43	614	5.76
0908	2	7	14	37	72	61	22	10	6	4	2	2	213	26	239	10.07
0909	32	58	116	324	521	406	190	90	57	43	31	28	1,615	280	1,895	27.26
0910	3	13	11	11	44	57	25	11	3	3	2	3	159	26	185	5.61
0911	80	75	60	52	83	114	48	44	36	39	63	82	433	345	778	8.94
0912	6	22	30	46	88	127	47	11	5	2	1	2	358	27	385	5.01
0913	4	14	23	30	66	108	51	16	7	5	4	4	293	38	331	8.29
0914	143	134	107	93	148	204	86	79	65	70	113	146	773	615	1,388	9.81
0915	37	35	28	24	39	53	23	21	17	18	30	38	202	161	363	11.86
0916	70	66	53	46	73	100	42	39	32	35	56	72	381	303	684	10.85
0917	106	126	146	195	391	533	302	141	96	69	83	106	1,693	601	2,294	10.20
Total	520	669	800	1,371	2,541	2,666	1,180	602	404	338	415	511	9,228	2,789	12,017	11.16

Remark : The sub basin code was referred in Table 2.1.

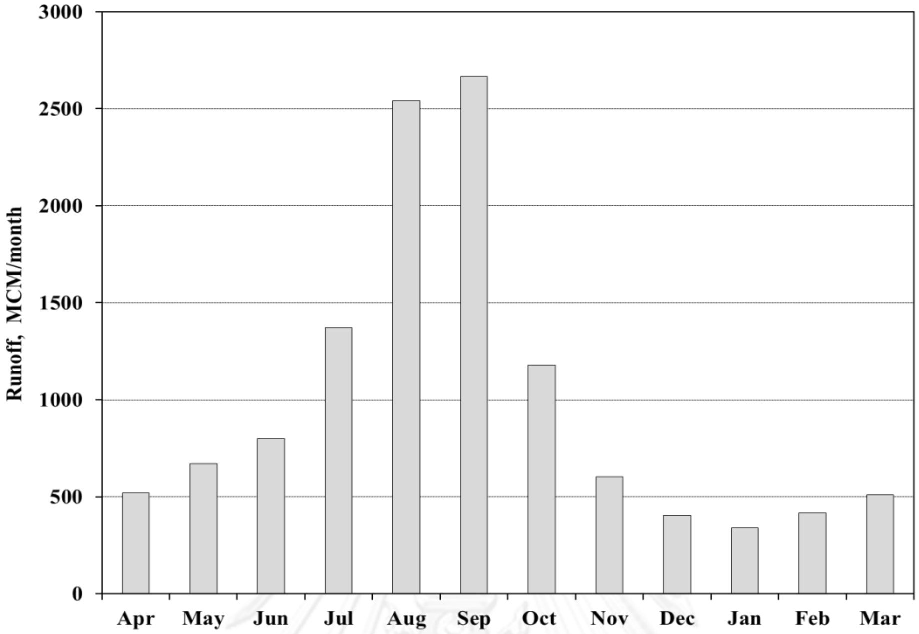
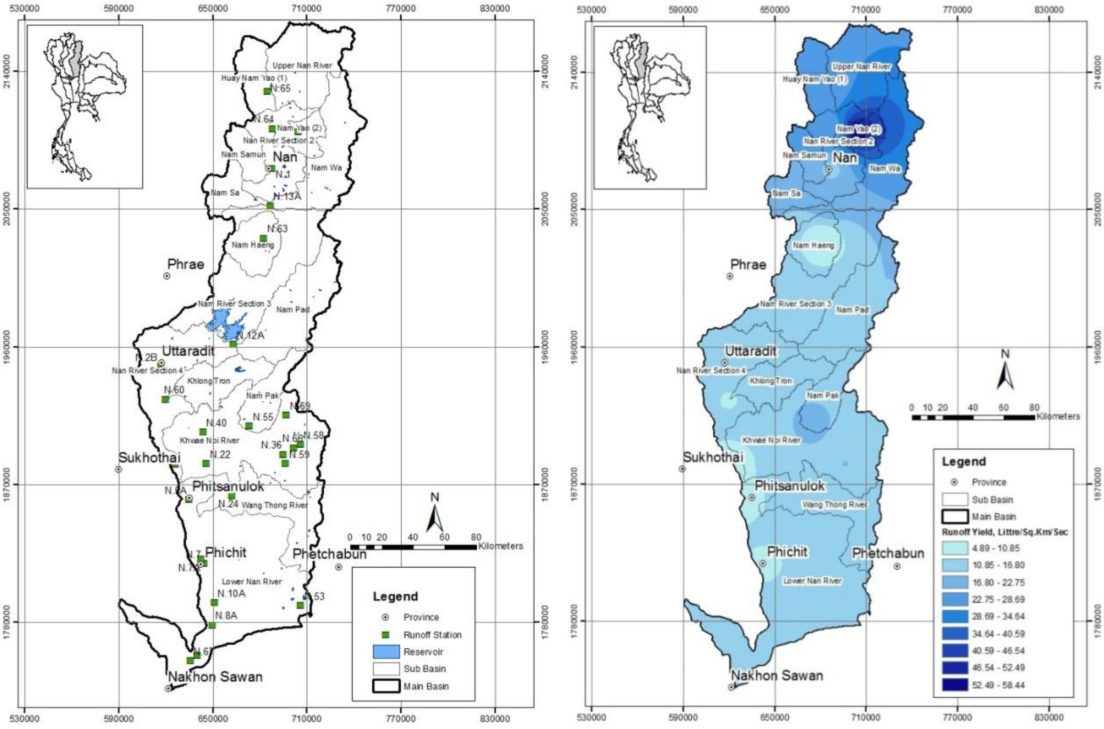


Figure 2.6 Average monthly runoff pattern of Nan river basin



a) Runoff gauge stations

b) Runoff yield

Figure 2.7 Locations of runoff gauge station and runoff yield in Nan River Basin

2.4 Land use

The land use map for 2005 was compiled by the Land Development Department (LDD). The land use of the Nan River Basin can be classified into 5 classes as shown in Table 2.5 and Figure 2.6. The present land use area in 2005 which can be classified into 5 major groups, is: agriculture (47.95%), urban and built-up land (2.20), water body (1.40%), forest land (46.30), and miscellaneous land (2.15%). The agricultural land utilization is mainly located in the Low Nan River Basin with coverage of 35% of the total agricultural area. The land use of the Nan River Basin is summarized in Table 2.5.

Table 2.5 Summary of land use in Nan River Basin in year 2005

Sub basin code	Sub basin name	Agriculture (Km^2)	Urban and Built-up land (Km^2)	Water body (Km^2)	Forest land (Km^2)	Miscellaneous land (Km^2)	Total Area (Km^2)
902	Upper Nan River	941.83	26.24	5.97	1,208.78	24.26	2,207.08
903	Huay Nam Yao (1)	188.84	3.19	0.94	449.77	217.71	860.46
904	Nan River Section 2	612.68	37.31	11.05	745.84	93.48	1,500.36
905	Nam Yao (2)	226.21	4.10	1.91	331.29	37.95	601.46
906	Nam Samun	206.77	9.56	0.32	393.57	8.48	618.70
907	Nam River Section 3	483.70	16.37	233.30	2,615.97	11.95	3,361.29
908	Nam Sa	111.17	3.17	2.79	610.01	19.97	747.11
909	Nam Wa	595.23	3.02	8.75	1,564.43	4.62	2,176.05
910	Nam Haeng	408.79	9.50	1.48	609.94	10.43	1,040.15
911	Nan River Section 4	1,835.21	182.96	84.69	517.28	12.82	2,632.96
912	Nam Pad	737.92	21.99	5.84	1,682.23	5.72	2,453.70
913	Khlong Tron	663.90	22.32	4.26	573.59	4.29	1,268.36
914	Khwae Noi River	2,512.27	49.12	25.18	1,865.36	12.07	4,463.99
915	Nam Pak	152.98	4.92	0.02	829.20	1.75	988.87
916	Wang Thong River	945.24	29.12	10.78	953.89	138.35	2,077.37
917	Lower Nan River	5,695.94	327.18	78.53	803.60	126.53	7,031.78
Total		16,318.69	750.07	475.83	15,754.75	730.36	34,029.70
%Proportion		47.95	2.20	1.40	46.30	2.15	100.00

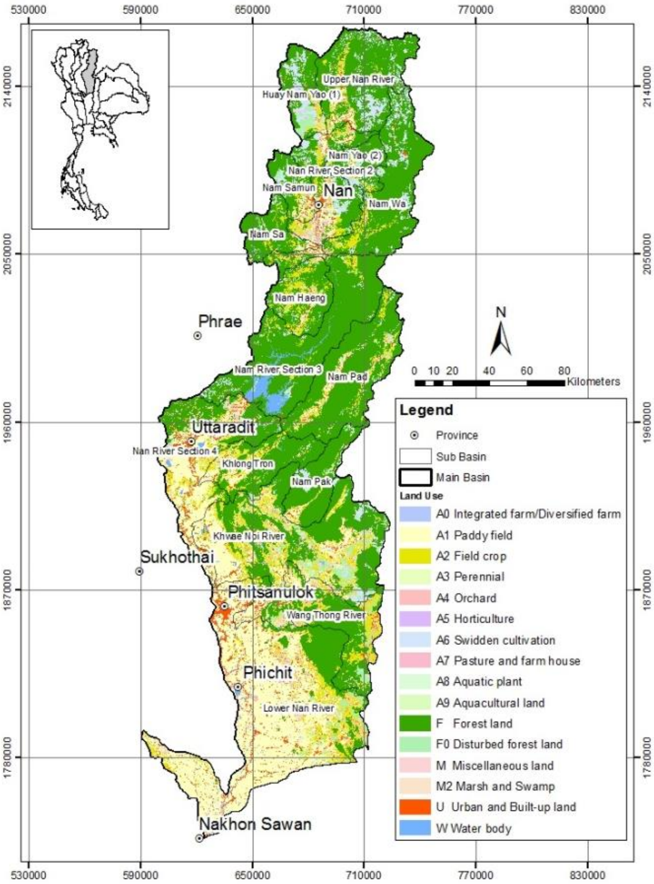


Figure 2.8 Land use in Nan River Basin

2.5 Irrigation development projects

The irrigation database was compiled by the RID in 2011 (RID, 2011). The water resource development projects undertaken in the Nan River Basin included large-, medium-, and small-scale projects. Furthermore, the pumping irrigation is regulated by the local authorities. The large-scale project is the Phitsanulok Irrigation Development Project, which received water from Sirikit Dam with a coverage area of 659,876 rais. (Note: 1 rai = 0.16 Hectare) This project includes the Naraesuan Dam O&M project (94,000 rais), the Plaichumbol O&M project (211,476 rais), the Dongsatti O&M project (186,000 rais), and the Thabua O&M project (168,400 rais). Concerning medium-scale water resource projects, there are 16 projects with a total combined active storage of 90.5 million m^3 and a total irrigated area of 229,650 rais. For the small-scale projects, there are 375 projects that have a total combined storage of 90.52 million m^3 and a total irrigated area of 329,646 rais. Of the pumping irrigation projects, there are 299 projects with an irrigated area of 389,010 rais. A summary of the irrigation projects is shown in Table 2.6.

Table 2.6 Summary of number and area of irrigation projects in Nan River basin

Sub basin code	Sub basin name	Medium		Small		Pumping	
		Number (projects)	Area (rais)	Number (projects)	Area (rais)	Number (projects)	Area (rais)
902	Upper Nan River	4	21,000	47	37,820	10	3,220
903	Huay Nam Yao (1)	-	-	9	4,750	-	-
904	Nan River Section 2	2	5,500	59	42,800	42	11,810
905	Nam Yao (2)	-	-	11	11,300	-	-
906	Nam Samun	1	10,000	20	11,390	1	180
907	Nam River Section 3	-	-	16	8,320	5	3,450
908	Nam Sa	1	11,000	8	1,200	-	-
909	Nam Wa	-	-	41	15,430	-	-
910	Nam Haeng	-	-	12	13,700	-	-
911	Nan River Section 4	3	82,400	39	77,469	90	169,370
912	Nam Pad	1	1,750	47	29,117	8	10,030
913	Khlong Tron	-	-	9	9,750	8	10,500
914	Khwae Noi River	-	-	25	18,650	44	60,670
915	Nam Pak	-	-	2	1,500	3	1,500
916	Wang Thong River	-	-	6	5,150	29	28,500
917	Lower Nan River	4	98,000	24	41,300	59	89,780
Total		16	229,650	375	329,646	299	389,010

Remark : The number and area of irrigation projects were compiled from RID database year 2011

2.6 Agriculture

2.6.1 Agriculture and cultivated area

The information of cultivated area of the Phisanulok Irrigation Project (PSK) and the Chao Phraya Irrigation Project (CP) were collected from RIO3 (year 1979 – 2008) and RID (year 2007). The total coverage area of the PSK and CP Projects is 666,400 rais and 7,542,822 rais, respectively. The agriculture area in the Phisanulok Irrigation Project included major rice, second rice, soy bean, garlic, peanut, maize, cassava, and sugarcane. The Chao Phraya Irrigation Project included major rice, second rice, sugarcane, fruit, perennial plants, fishing ponds, crops and vegetables. The cultivated area of the PSK and CP Projects is shown in Table 2.8 and Table 2.9.

Table 2.7 Summary of the cultivated area of Phisanulok Irrigation Project

Irriagtion project	District	Province	Wet (rais)		Dry (rais)	
			Rice	Crop	Rice	Crop
1. Naraesuen Dam O&M Project	Phrom Phiram	Phisanulok	79,768	59	72,773	763
2. Plaichumpol O&M Project						
2.1 Plaichumpol O&M Project	Maung Phisanulok	Phisanulok	169,862	0	159,009	47
2.2 Plaichumpol O&M Project	Muang Phichit	Phichit	18,859	29,420	24,871	29,467
3. Dong Setti O&M Project	Muang Phichit	Phichit	162,614	0	164,167	509
4. Tha Bua O&M Project						
4.1 Tha Bua O&M Project	Pho Talae	Phichit	118,447	0	150,424	266
4.2 Tha Bua O&M Project	Muang Nakhon Sawan	Nakhon Sawan	5,091	0	9,579	36
Total			554,640	29,479	580,823	31,087

Table 2.8 Summary of the cultivated area of Chao Phraya Irrigation Project

Project area	Irrigation Area (rais)	Average cultivated area		Percentage of planting[1/]						
		Wet (rais)	Dry (rais)	Wet		Dry			Total	
				Rice	Perennial	Rice	Crop	Vegetable	Wet	Dry
Upper East Bank	1,392,874	1,337,300	265,665	98.2	1.8	17.7	2.6	0.3	100.0	22.4
Lower East Bank	2,514,240	1,960,677	945,771	85.7	14.2	29.1	0.3	0.2	100.0	43.9
Upper West Bank	2,157,782	1,981,733	1,003,896	92.3	7.8	40.9	1.2	0.2	100.0	49.9
Lower West Bank	1,477,926	1,148,221	978,851	96.9	3.1	35.8	0.5	5.7	100.0	40.8
Overall Sum	7,542,822	6,427,931	3,194,183	93.0	7.0	30.9	1.2	1.6	100.0	33.6

Remark : 1/ The percentage of planting area was calculated from the cultivated area devided by the average cultivated area in wet season
2/ Upper East Bank Irrigation Projects include Monorom, Chongkhae, Khok Kratheim, Khok Kratheim, Rueng Rang, Maha Ratcha
Lower East Bank Irrigation Projects include South Pasak, Tha Luang, North Rangsit, South Rangsit, Khlong Dan, Phra Ong Chaiya
Upper West Bank Irrigation Projects include Phola thep, Borom That, Chana Sut, Yang Mani , Pak Hai, Tha Bote, Sam Chuk, Pho Phraya, Pholathep, Tha Bote, Don Chedi
Lower West Bank Irrigation Projects include Bang Bal, Pak Hai, Chao Chet-Bang Yeehon, Phraya Banlu, Phra Pimon, Phasi Charoen

2.6.2 Cropping pattern

The cropping patterns were reviewed by the Department of Water Resources (DWR, 2005). In the Nan River Basin, the farmers mostly start to cultivate major rice in the early May and harvest in the middle of November, while they start to cultivate second rice in early-December and harvest in mid-April. The cropping pattern in the Nan River Basin and the Lower Chao Phraya River Basin is shown in Table 2.9 and Table 2.10.

Table 2.9 The cropping pattern in irrigated area in Nan River basin (Phitsanulok Irrigation Project)

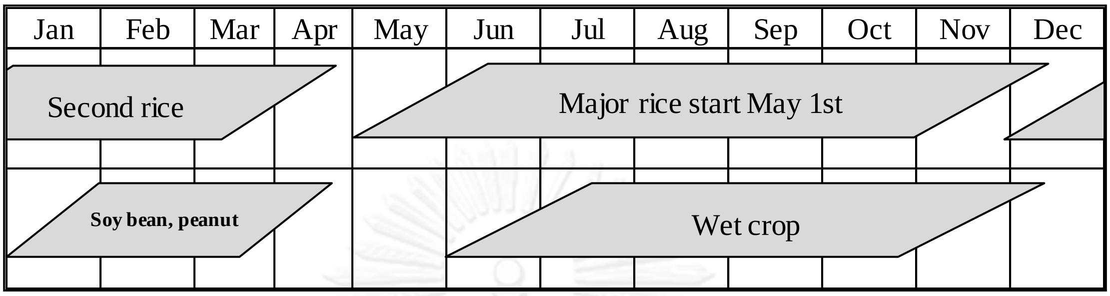
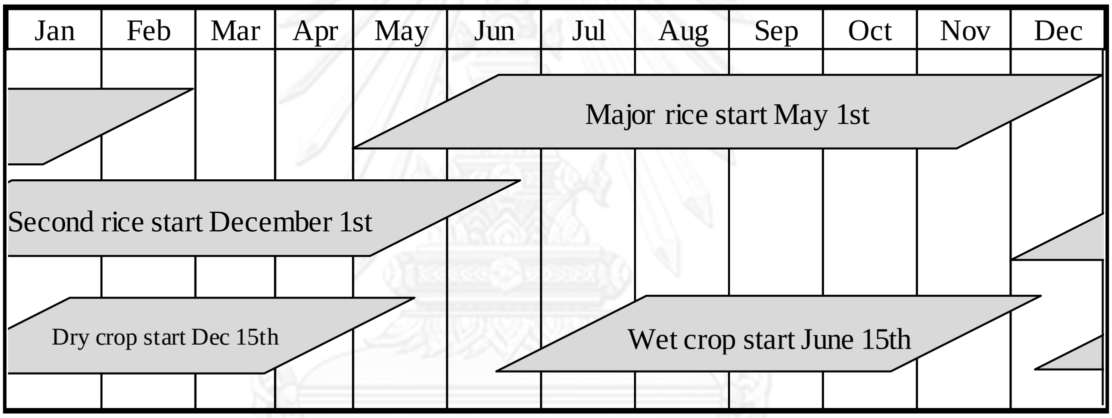


Table 2.10 The cropping pattern in irrigated area in Chao Phraya River basin



2.7 Existing water usage

The existing water usage was compiled and estimated from the necessary information from the related government agencies. The main water users included domestic, industrial and agricultural, respectively. A summary of the water usage is shown in Table 2.11.

1) Domestic water usage

The domestic water usage was estimated from the population in the Nan River Basin compiled from the Department of Provincial Administration (DPA) in 2010 and the domestic water consumption rate. The total domestic water usage is about 60.63 MCM/year, and the proportion of domestic water usage is about 1.72% of total water usage.

2) Industrial water usage

The industrial water usage was estimated from the registered horse power of the factories from the Department of Industrial Works (DIW) in 2010 and the industrial water consumption rate. The total industrial water usage is about 10.19 MCM/year and the proportion of industrial water usage is about 0.29% of total water usage.

3) Agriculture water usage

The agriculture water usage was estimated from the evapotranspiration, the crop coefficient, the cultivated area and the cropping pattern. The agriculture water usage can be separated into 2 types of cultivated area: the irrigated area and the rain-fed area. The irrigated area was collected cultivated area data from Royal Irrigation Department (RID) database, while the rain-fed area was collected cultivated area data from Office of Agricultural Economic (OAE). The total agriculture water usage is about 3,454.38 MCM/year and the proportion of agriculture water usage is about 98% of total water usage.

Table 2.11 Summary of water usage in Nan River Basin

Sub basin code	Sub basin name	Water usage (MCM/year)			
		Domestic	Industrial	Agriculture	Total
902	Upper Nan River	2.48	0.10	72.13	74.71
903	Huay Nam Yao (1)	0.47	0.11	4.48	5.06
904	Nan River Section 2	4.03	0.04	71.34	75.41
905	Nam Yao (2)	0.35	0.01	10.75	11.11
906	Nam Samun	0.64	0.40	24.41	25.46
907	Nam River Section 3	1.34	0.04	24.05	25.44
908	Nam Sa	0.33	0.23	17.83	18.39
909	Nam Wa	0.77	0.01	20.60	21.38
910	Nam Haeng	0.75	0.01	17.59	18.35
911	Nan River Section 4	11.05	1.80	902.36	915.21
912	Nam Pad	1.01	0.03	73.44	74.48
913	Khlong Tron	0.95	0.20	50.27	51.42
914	Khwae Noi River	4.36	0.80	239.19	244.34
915	Nam Pak	0.45	0.01	8.24	8.70
916	Wang Thong River	2.42	0.38	102.21	105.01
917	Lower Nan River	29.22	6.02	1815.49	1850.73
Total		60.63	10.19	3454.38	3525.20
Propotion (%)		1.72	0.29	97.99	100.00

Remark : Water usage was calculated from the population, factory information and cultivated area in year 2010

2.8 Flood problems

Regarding the upper area of Sirikit Dam, the flooding damage in the Nan river basin and downstream of the sub-river basin at Nan Municipality were caused by a narrowing of the retaining wall and fast overland flood in flood plain. These areas cultivated short-season agriculture crops. For lower area of Sirikit Dam, the water flow usually does not spill over the river banks due to the Sirikit Dam reservoir, which can absorb the flood volume from upstream. However, floods usually take place on downstream of the sub-river basin, such as at the Nam Pad, Khwae Noi, and Wang Thong rivers and downstream from the Nan sub-river basin. Flood water usually inundates the lower part of the sub-river basin which is a flood plain, and living areas such as Phitsanulok and Pichit municipality or good agricultural areas when the water in the Nan River is at a high level (RID, 2005). The result of the severity problem analysis shows that Wang Thong and Lower Nan sub-river basins have the highest severe flood problem level. Flooding in the Nan river basin is caused by the following:

a) Regarding the topography of the basin, the capacity of the Nan River cannot carry over a high amount of runoff during the flooding period because the upper part of the river channel at Muang Uttaradit (160 m river width with capacity 5,000 m3/s) is wider than the lower part at Maung Phitsanulok (127 m river width with a capacity of 1,500 m3/s).

b) High intensity rainfall at the upper and lower Nan River.

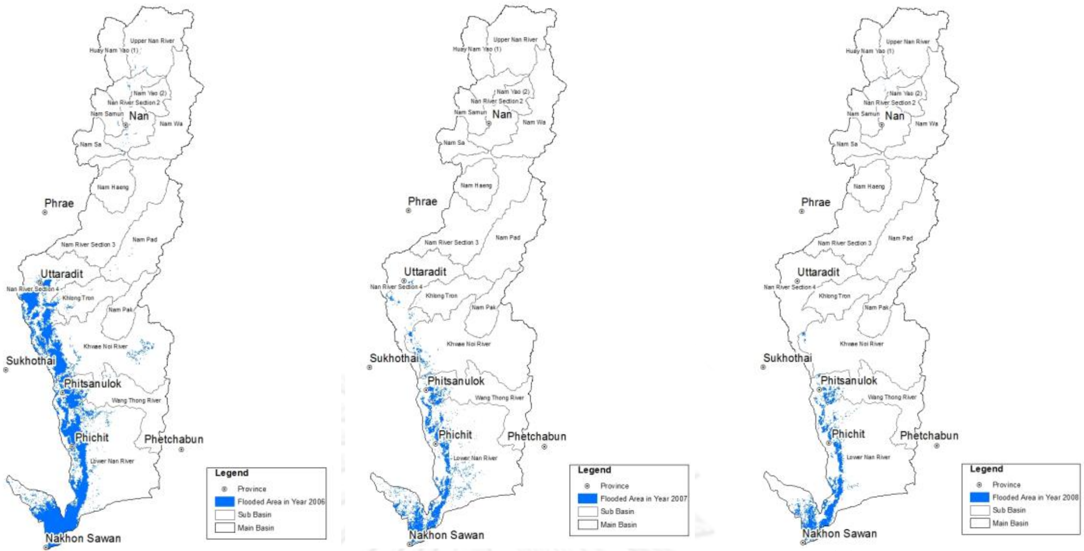
c) Flood water from the Yom River flowed crosses into the Nan River through a diversion channel.

d) The inundation water of the low land could not drain through the Lower Chao Phraya Basin because the floodplain retains the flooded water.

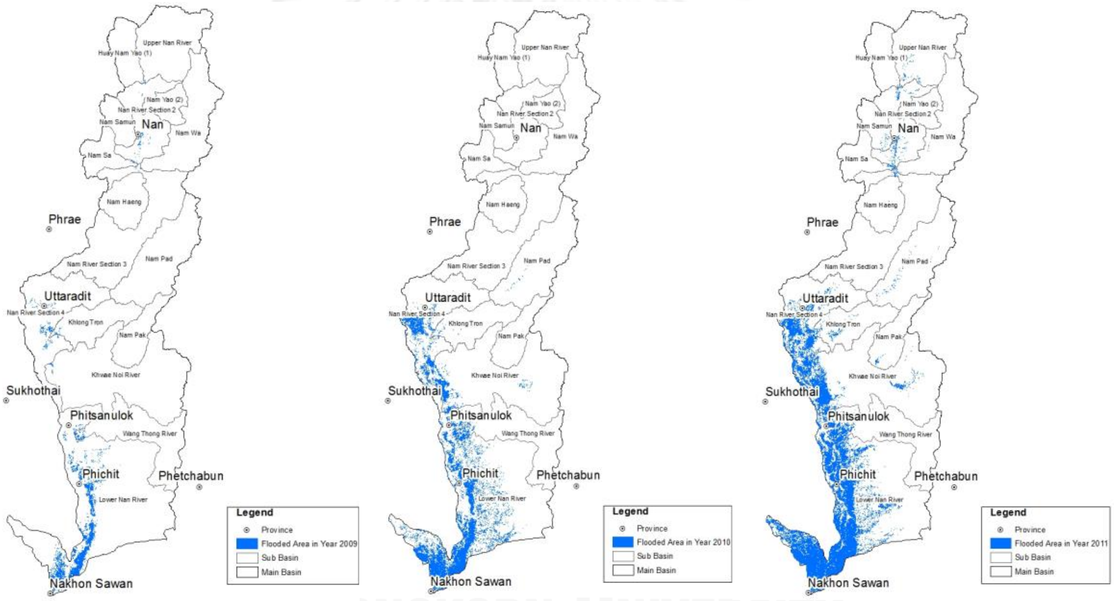
The flooded area in the Nan River Basin was estimated the flooded area from the GISTDA’s satellite map as shown in Table 2.12 and Figure 2.9. Within the last 10 years, there were 6 flood events that caused the losses and damage in the Nan River Basin. A huge flood event occurred in 2011, and the inundated area was about 3,952 Km^2. Mostly of the flooded area was in the lower Nan River Sub-Basin, and the coverage area was about 68% of the total flooded area. Furthermore, the inundated area was located on both sides of the Nan River banks, covering Uttaradit Province through Nakhon Sawan Province.

Table 2.12 Summary of the flooded area in Nan River Basin

Sub basin code	Sub basin name	Flooded area (Km^2)					
		2006	**2007**	**2008**	**2009**	**2010**	**2011**
902	Upper Nan River	4.74	-	2.63	0.55	-	17.57
903	Huay Nam Yao (1)	0.14	-	0.75	0.85	-	1.71
904	Nan River Section 2	9.72	-	1.79	15.86	0.02	56.18
905	Nam Yao (2)	-	-	-	-	-	1.95
906	Nam Samun	1.36	-	-	0.86	-	11.25
907	Nam River Section 3	0.46	-	-	2.15	0.16	9.44
908	Nam Sa	1.27	-	-	2.28	0.04	5.42
909	Nam Wa	-	-	-	0.15	-	3.53
910	Nam Haeng	0.62	-	-	0.29	-	3.50
911	Nan River Section 4	616.00	41.80	0.55	50.33	329.58	631.44
912	Nam Pad	3.03	-	-	-	5.58	17.61
913	Khlong Tron	46.45	0.63	-	5.20	8.66	54.38
914	Khwae Noi River	411.31	64.14	7.01	4.42	190.60	378.88
915	Nam Pak	-	-	-	-	-	9.62
916	Wang Thong River	83.09	43.52	37.67	14.24	50.24	75.93
917	Lower Nan River	1,863.73	989.53	824.22	622.53	1,725.86	2,674.02
Total		3,041.91	1,139.61	874.62	719.69	2,310.73	3,952.45



(a) year 2006 (b) year 2007 (c) year 2008



(d) year 2009 (e) year 2010 (f) year 2011

Souce : The flooded area was contributed by GISTDA, 2012

Figure 2.9 Flooded area in Nan River Basin

2.9 Existing water management

2.9.1 Existing reservoir operation

Sirikit Dam is a multi-purpose reservoir project. It is an earth dam whose height is 113.6 m, with a crest level at 169 m MSL, and is located on the

Nan River at Amphoe Thapla, Changwat Uttraradit. It was established in 1971, with a reservoir capacity of 9,510 MCM, a watershed area of 13,086 Km^2, a normal storage level at 162.0 m MSL, two tunnel spillways diameter of 11 m, a maximum release of 3,250 m^3/s, and an annual inflow of 6,695 Mm^3. At present, the Sirikit hydropower plant has installed 4 generators, with a capacity of 125 MW, for a total of 500 MW, and generated electricity of 1,245 million KW/hour. The watershed area of Sirikit Dam is 13,130 km^2. The traditional dam operations of Sirikit Dam have been carried out conjunctively with Bhumibol Dam in the Ping River to allocate water to the Chao Phraya Basin. The water release from Sirikit Dam supplies the agriculture in the Phitsanulok Irrigation Project (around 96,000 ha, as shown in Figure 2.1) and to the irrigation projects (around 1,200,000 ha in the wet season and 480,000 ha in the dry season) in the Chao Phraya Basin, conjunctively with Bhumibol Dam. The Sirikit Dam is a multipurpose reservoir and the storage water is used in the following order of priority : irrigation for agricultural areas in the Lower Nan River Basin and Chao Phraya River Basin, flood mitigation, fisheries, water transportation, maintaining the downstream ecosystem, and electricity generation (EGAT, 2005).

The existing rule curves were collected from the Electricity Generating Authority of Thailand (EGAT) and is shown in Figure 2.10. There are 2 sets of reservoir operation rule curves, including the existing reservoir operation rule curves (called general rule curves) and the revised 2012 operation rule curves (called flood rule curve) suggested by the government of Thailand. The water level under the existing reservoir operation is shown in Figure 2.10. Even though the reservoir operator attempted to regulate the water level close to the reservoir operation rule curve. The actual practices could not follow the standard rule curve set up by the RID office. As can be seen in Figure 2.11, there are 254 months or 59% of the total operation times (432 months) under the existing lower rule curve. According to the results, the reservoir operators had to judge how to release the water in the existing or actual situation rather than following the reservoir operating rules. Consequently, this study focuses on how to deal with the actual situation, which emphasizes that the reservoir operations need to be improved accordingly.

Table 2.13 Existing and revised 2012 reservoir operation rule curves

Rule Curve	Storage, MCM											
	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Existing												
URC	8,244	7,771	7,372	7,208	7,290	8,111	9,016	9,510	9,510	9,502	9,240	8,854
LRC	6,396	6,102	5,829	5,718	5,773	6,312	6,835	7,125	7,125	7,120	6,967	6,750
Revised 2012												
URC	8,024	7,207	6,584	6,115	6,170	7,601	8,819	9,473	9,510	9,494	8,996	8,532
LRC	4,899	4,241	4,041	4,216	4,452	5,401	6,424	6,791	6,558	6,405	6,106	5,547

Remark : URC = Upper rule curve, LRC = Lower rule curve

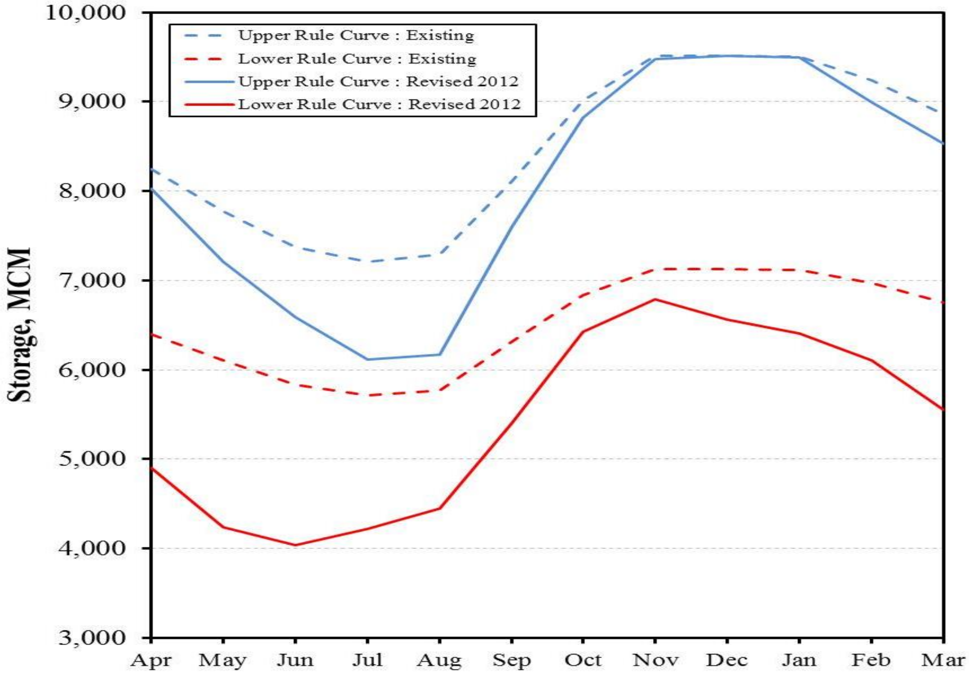
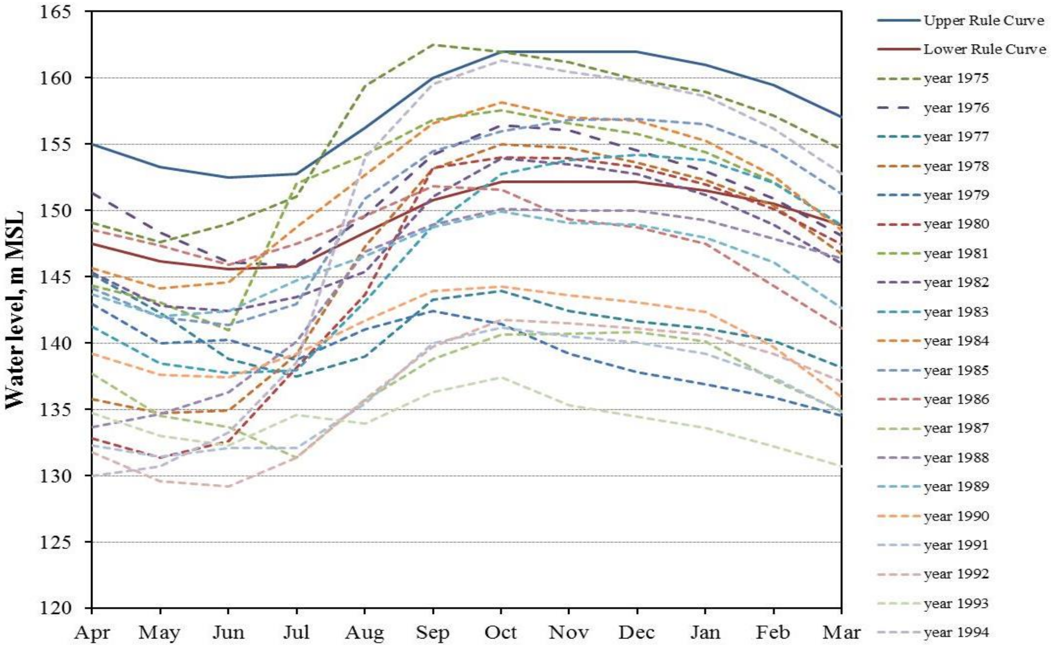
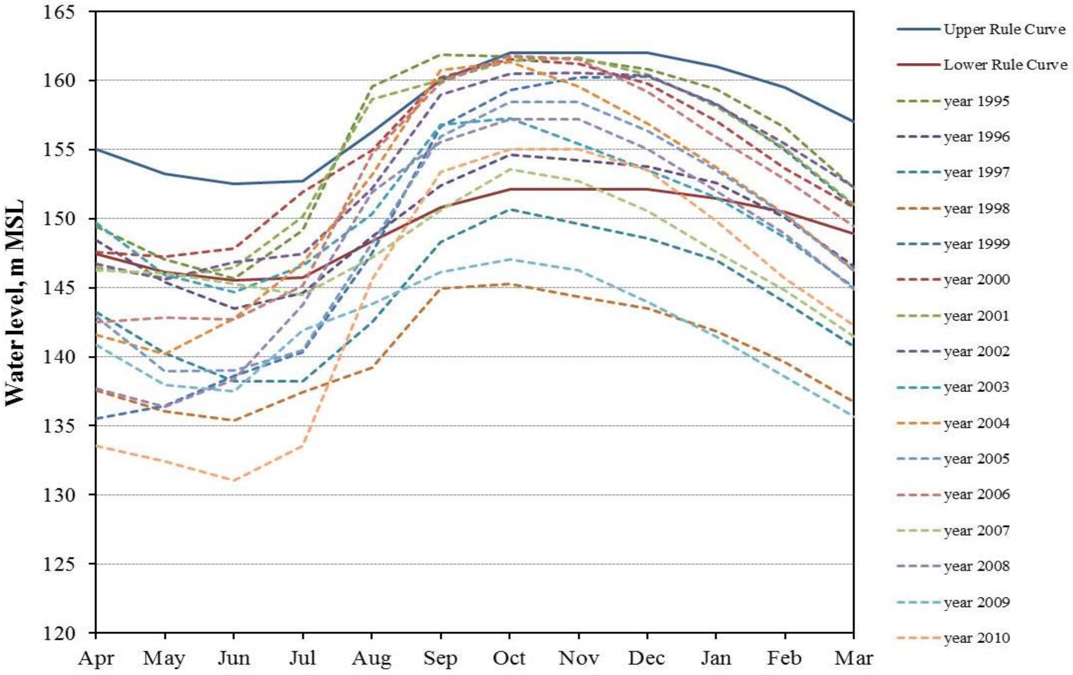


Figure 2.10 Existing and revised 2012 reservoir operation rule curves of Sirikit Dam



(a) Water level in year 1975 – 1994



(b) Water level in year 1995 - 2010

Figure 2.11 The dam water level under the existing reservoir operation

2.9.2 Existing water allocation

The water allocation in the early dry season (November) determines water usage for each activity to be allocated according to the water budget. Thus, the water allocation was planned by the Royal Irrigation Department and Electricity Generation Authority of Thailand as a guideline for water allocation during the cultivation season and protected the conflict among the water users. However the water budget for the Phitsanulok and Chao Phraya Irrigation Projects depend on the total water budget for Bhumibol and Sirikit Dam. The water allocation planning will be considered based on the water budget of both dams at the end of the wet or dry season (RID, 2008). The water budget for reservoir regulation which the RID and EGAT carried out as water allocation criteria is shown in Table 2.14.

Table 2.14 The water year criteria of Bhumibol and Sirikit Dam (at November)

Water allocation criteria	Water Budget (MCM)	
	Bhumibol and Sirikit dam	Phitsanulok Irrigation Project
High water year	> 10,000	> 800
Normal water year	6,000 - 10,000	500 - 800
Dry water year	4,000 - 6,000	200 - 500
Very dry water year	< 4,000	< 200

Regarding the water allocation of Phitsanulok Irrigation Project was analyzed from 1975 to 2010. The water budget of Bhumibol and Sirikit Dam was classified according to the water year criteria, as shown in Figure 2.12. The results show that the water year for both dams can be classified into high water year, normal water year, dry water year and very dry water year during 7-year, 20-year, 4-year and 5-year periods, respectively. On the other hand, the comparison of the actual water allocation of the Phitsanulok Irrigation Project and the water allocation criteria revealed that the water allocation during the dry season was in line with the criteria of 19% of the regulated times, over line with the criteria 4% of the regulated times and under line with the criteria 78% of the regulated times.

A comparison of the water allocation for the Phitsanulok Irrigation Project during the wet and dry seasons with the water year criteria is shown in Figure 2.13 and Figure 2.14. The wet and dry season begin at May to October and November to April, respectively. It was found that the water year in the wet season was in line with the criteria of 52% of the regulated time, over line with the criteria 30% of the regulated times and under line with the criteria 18% of the regulated times. Furthermore the comparison of the water allocation and water demand revealed that the water allocation was insufficient to supply the water demand, which the average water deficit was 531.46 MCM/year. The average water deficit during the wet and dry season was 384.59 MCM/year and 146.87 MCM/year, respectively. According to the results, it can be implied that the water regulators allocated the irrigated water more effectively during the wet season than during the dry season. However, it is necessary for the water allocation during dry season to be revised according to the water demand; otherwise, the water shortage event will occur more frequently in the future. A comparison of the water allocation and water demand in wet and dry seasons is shown in Figure 2.15 and 2.16. It was revealed that the water management of this irrigation has to be adjusted to match the supply and demand. For this reason, the water allocation rule of this irrigation project will be taken into account to make a decision for water allocation.

Due to the monthly actual regulation, the storage of the reservoir has a chance to be overflowed through the spillway, so the risk of dam failure has to be considered. Normally, the flood peak regulation case, the dam operator will open the spillway gates before the flood peak volume overflow the crest of spillway. For above reasons, this study considered the water overflow level according to the average overflow level that occurred in the historical dam operations. The average overflow level was 161.90 m MSL or 9,485 MCM, which also can be identified as the maximum limitation of the dam capacity. In contrast, the minimum limitation of the dam is the dead storage level, where the water level is 128 m MSL or 2850 MCM.

The general dam operations are as follows. If the water level is over the average overflow level, the water will overflow the spillway. On the other hand, the reservoir will not release water if the water level is under the dead storage level. The characteristic of Sirikit and Bhumibol Dam were considered from the height-area-volume relation, maximum, normal and minimum storage, and upper and lower rule curve. Therefore, this reservoir operation in this study was considered under the dam characteristic and practical operations or "business as usual". Some information was obtained from the interviews with the dam operators, whose main concern is that release should be sufficient for fisheries activities during wet season, when at least 6 – 7 Mm^3/day is released, while the controlling discharge at the Chao Phraya diversion dam should be at least 80 m^3/sec. Furthermore the dam operator suggested enhancing the efficiency of the release during the dry season for irrigation and for fishery activities and in the wet season for flood control downstream. For the above reasons, the constraints of dam regulation will be taken into account with the release rule in this study also.

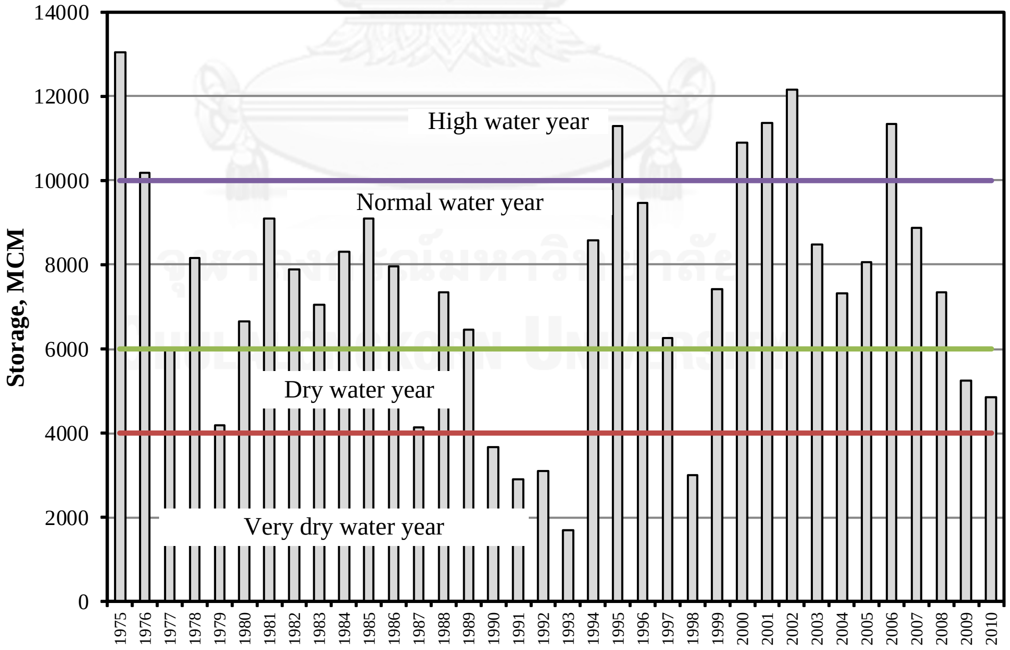


Figure 2.12 The comparison of water budget of Bhumibol and Sirikit Dam and water year criteria (at November)

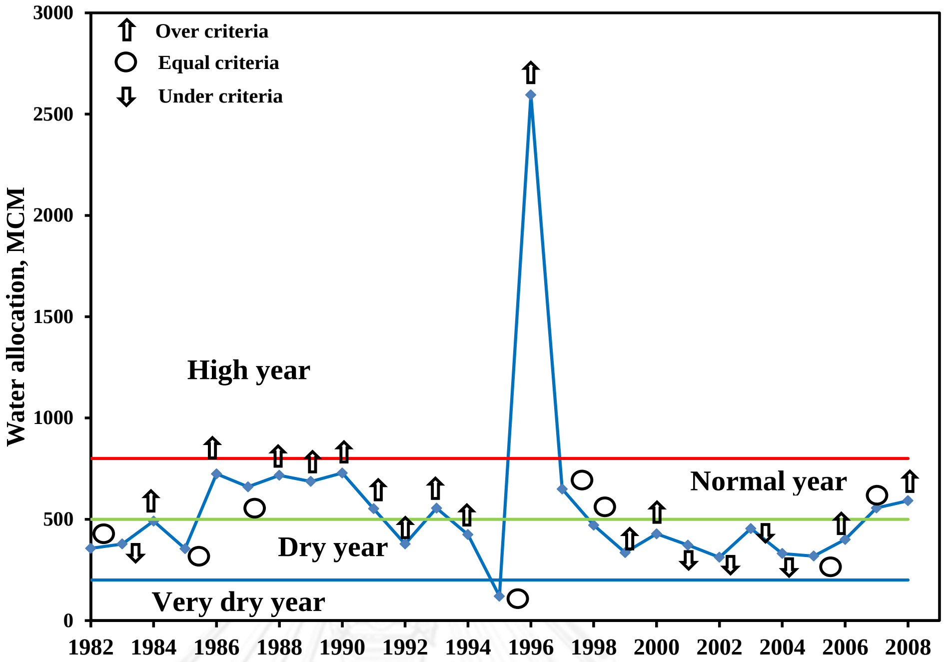


Figure 2.13 The comparison of water allocation of Phitsanulok Irrigation Project in wet season with the water year criteria

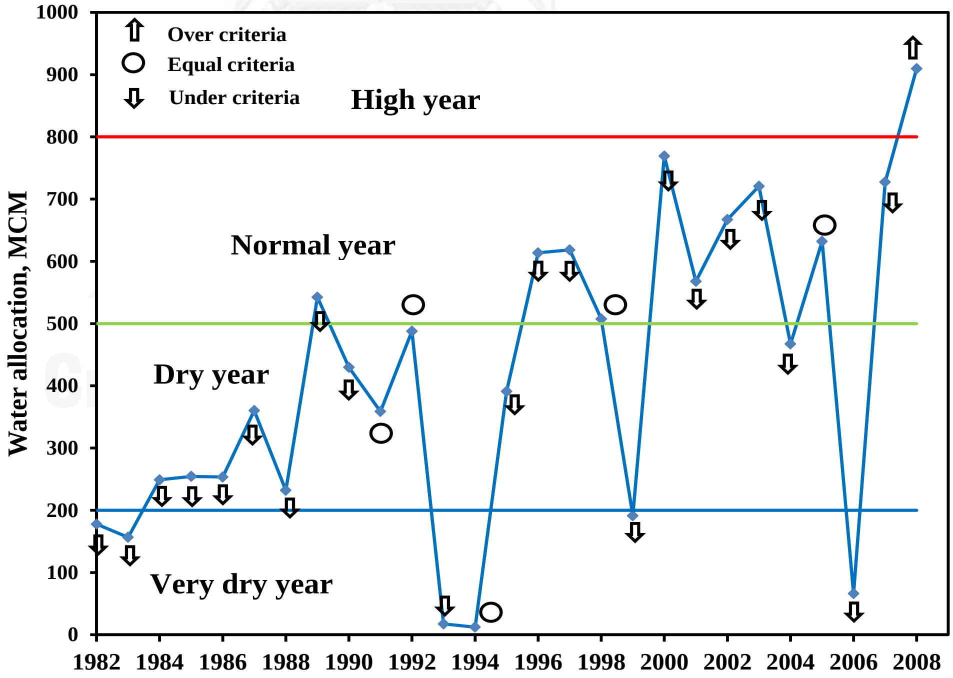


Figure 2.14 The comparison of water allocation of Phitsanulok Irrigation Project in dry season with the water year criteria

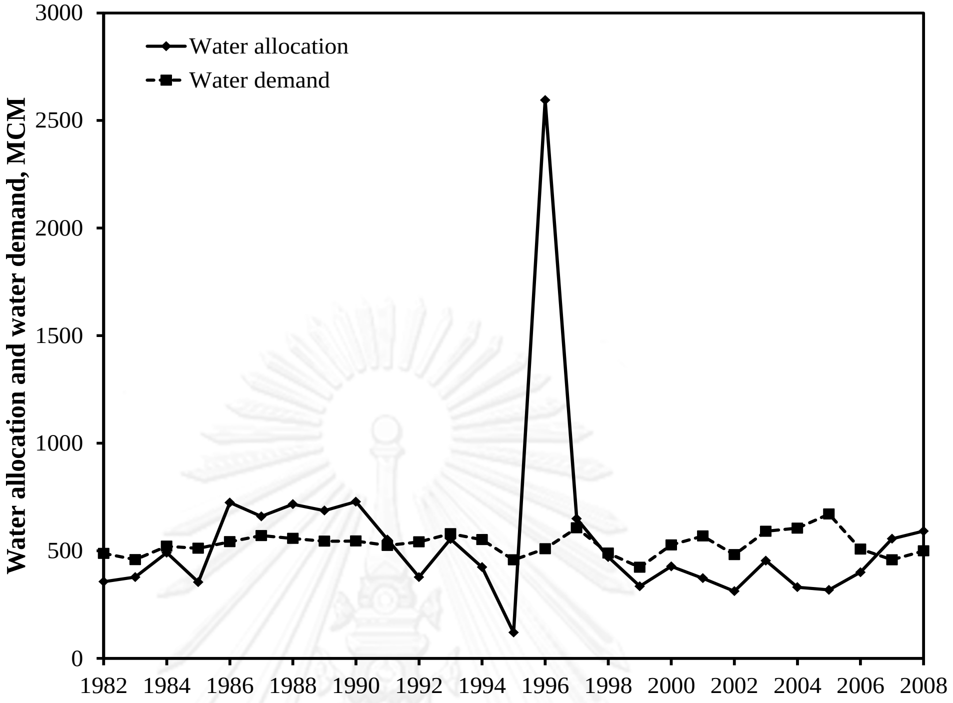


Figure 2.15 The comparison of water allocation and water demand of Phitsanulok Irrigation Project in wet season

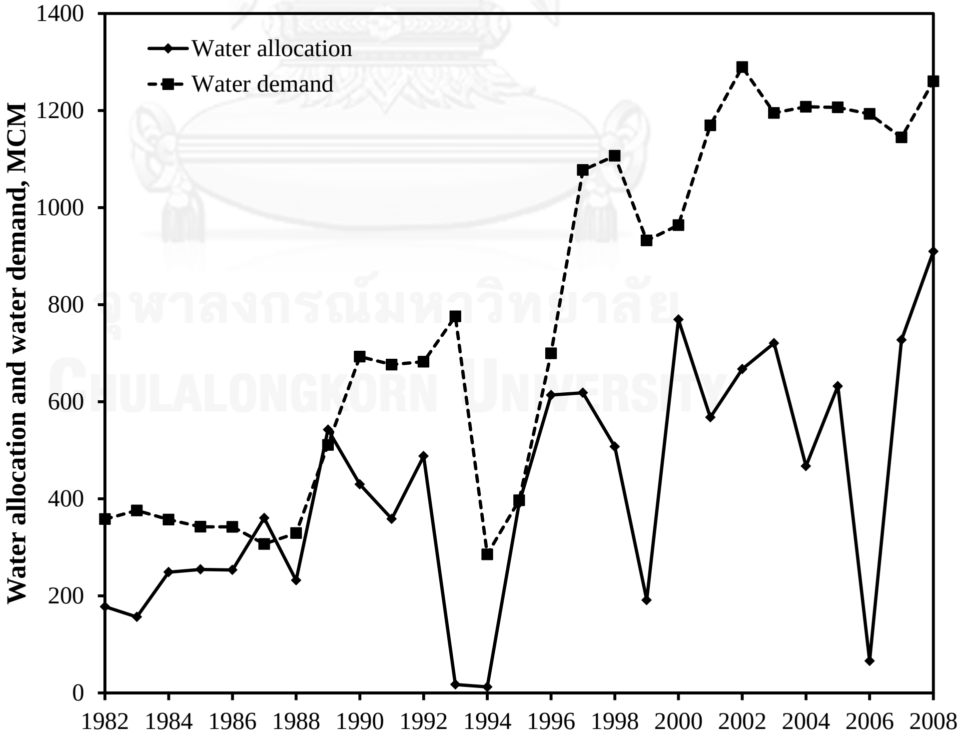


Figure 2.16 The comparison of water allocation and water demand of Phitsanulok Irrigation Project in dry season

CHAPTER III
LITERATURE REVIEW

The references from the literature review for this thesis includes GCM selection, bias correction of GCM precipitation, rainfall-runoff model, decision analysis and reservoir operation approaches. The summary is shown as follows:

3.1 GCM selection

Sperber and Palmer (1996) evaluated the interannual variability of rainfall on the Indian subcontinent, the African Sahel, and the Nordeste region of Brazil in 32 models of the Atmospheric Model Intercomparison Project (AMIP). They found that the interannual variations of Nordeste rainfall were the most readily captured and the precipitation variations in India and the Sahel were less well simulated.

Gadgil and Sajani (1998) presented an analysis of the seasonal precipitation associated with the African, Indian and the Australian-Indonesian monsoon and the interannual variation of the Indian monsoon simulated by 30 atmospheric general circulation models of the Atmospheric Model Intercomparison Project (AMIP). The seasonal migration of the major rain belt observed in the African region was reasonably well simulated by almost all the models.

Kang et al. (2002) assessed the overall performance of state-of-the-art atmospheric GCMs in simulating the climatological variations of summer monsoon rainfall in the Asian-Western Pacific region and systematic errors. The GCM data utilized were obtained from 10 GCM groups participating in the CLIVAR/Monsoon GCM Intercomparison Project. The model composite shows that the overall spatial pattern of summer monsoon rainfall was similar to the one observed, although the western Pacific rainfall was relatively weak.

Waliser et al. (2003) analyzed the intraseasonal variability associated with the Asian summer monsoon as simulated by a number of atmospheric general circulation models (AGCMs). They focused on the spatial and seasonal variations associated with the intraseasonal variability (ISV) of rainfall in the term of the spatial-temporal variation of rainfall [i.e. their depiction of the Intraseasonal Oscillation (ISO)], the teleconnection patterns associated with each model's ISO, and the implications of the models' ISV for seasonal monsoon predictability. The results showed that several of the models exhibit ISV levels at or above that found in observations with the spatial patterns of ISV that resembled the observed pattern.

Annamalai et al. (2007) examined the relationship between ENSO and monsoons using interannual and decadal time scales from 18 GCM models. They found that six of the 18 models had a reasonably realistic representation of monsoon precipitation climatology.

Kripalani (2007) examined the South Asian summer monsoon precipitation and its variability from the outputs of the 22 coupled climate models. They found that 19 models were able to capture the maximum rainfall during the summer monsoon period (June through September) with varying amplitude. While two models were unable to reproduce the annual cycle well, one model was unable to simulate the summer monsoon season.

Sharma (2007) compared the statistical parameters of the six GCMs precipitation and temperature (17 experiments) with the observed values to select the suitable GCM data for the impact assessment of climate change on water resources. The six GCMs include HadCM3, CCCma, CSIRO-MK2, GFDL-R30, US NCAR and ECHAM4. The results revealed considerable variability regarding the various GCM simulations for the observed climate. The HadCM3, ECHAM4, GFDL-R30 and US NCAR models are good at simulating the magnitude and spatial variability of mean temperature. The precipitation comparisons showed much higher variations than those for the mean temperature for all models and all stations. The CSIRO-

MK2 and ECHAM4 model are good representations of the term of magnitude and spatial variability of precipitation.

Lin et al. (2008) evaluated the subseasonal variability associated with the Asian summer monsoon in 14 coupled general circulation models (GCMs) participating in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). The results showed that current state-of-the-art GCMs still had difficulties and displayed a wide range of skill in simulating the subseasonal variability associated with the Asian summer monsoon.

Bollasina and Nigam (2009) examined the veracity of modeled air–sea interactions in the Indian Ocean during the South Asian summer monsoon. They analyzed the air–sea interactions from the coupled general circulation models as part of the Intergovernmental Panel on Climate Change Fourth Assessment Report. The results showed that the presence of large systematic biases in coupled simulations of boreal summer precipitation, evaporation, and sea surface temperature (SST) in the Indian Ocean, often exceeding 50% of the climatological values.

Rajeevan et al. (2012) compared the performance of the new multi-model seasonal prediction system developed in the frame work of the ENSEMBLES EU project for the seasonal forecasts of India summer monsoon variability and the results from the previous EU project, DEMETER. The results showed systematic biases in the representation of mean monsoon seasonal rainfall in the Indian region, which were similar to that of DEMETER. The ENSEMBLES coupled models are characterized by an excessive oceanic forcing on the atmosphere over the equatorial Indian Ocean.

Sperber et al. (2013) evaluated the boreal summer Asian monsoon in 25 Coupled Model Intercomparison Project-5 (CMIP5) and 22 CMIP3 GCM simulations of the late twentieth century. This statistic inferences were used to evaluate which included the diagnostics and skill metrics to assess the time-mean, climatological annual cycle, interannual variability, and intraseasonal variability. They pointed out that there is no single model that best represents all of these aspects of the monsoon. The CMIP5 multi-model mean (MMM) was more skillful than the CMIP3 MMM for all diagnostics in terms of the skill metrics with respect to observations.

3.2 Bias correction of GCM climate and precipitation

Bias is defined as the time independent component of the error. It is well known that some form of pre-processing is necessary to remove biases present in the simulated climate output fields before they can be used for hydrological modeling. The bias correction methods are used to remove the bias from GCM data such as quartile mapping, gamma-gamma transformation, regression-based and hybrid method. The bias correction method is reviewed in the following.

Chen et al. (2000) applied the Lamont model to demonstrate that the biases from raw GCM output can be effectively reduced with a simple statistical correction, and the bias-corrected model can have a more realistic internal variability as well as an improved forecast performance.

Shrestha et al. (2004) used the non-homogenous multiplicative random cascade method to downscale the spatial rainfall field. The Hierarchical and Statistical Adjustment (HSA) method has been introduced and tested in this study to downscale 1.25 degree GAME Re-analysis data into 10-minute spatial resolution. From the evaluation of the statistics of 30 realizations, it was found that the random cascade method was able to conserve the accumulation mass according to its initial assumption. The accumulated mass conservation of the generated rainfall field was erroneous while viewed for a particular catchment in different grid-size systems.

Tantanee (2005) developed the Downscaled Rainfall Prediction Model (DRPM) using the technique of unit disaggregation curve (UDC). This technique coupled the concept of stochastic autoregressive (AR) model with a wavelet filter and disaggregation model.

Zehe et al. (2005) used a stochastical approach for generating rainfall time series based on objective circulation patterns (CP). This method was applied to the mesoscale Anas catchment in northwest India. The time scale as well as the frequency distribution of the monthly rainfall at different stations were captured and performed well. Correlation coefficients between simulated and observed monthly rainfall were larger than 0.85 at each station. Furthermore, the additional predictors such as SST anomalies and wind direction classes were also introduced in this paper to bring substantial model improvements.

Ines and Hansen (2006) proposed the use of gamma distribution to represent observed rainfall intensity, and applied both gamma and empirical distributions to correct the bias of GCM rainfall intensity. At the study site, the proposed bias correction methodology was applied to correct the bias of both the mean and variance of monthly and seasonal GCM rainfall, including frequency and mean. All of the bias correction procedures improved maize yield simulations, but resulted in substantial negative mean bias. This bias appears to be associated with a tendency for the GCM rainfall to be more strongly autocorrelated than observed rainfall, resulting in unrealistically long dry spells during the growing season.

Hashino et al. (2006) evaluated three bias-correction methods for ensemble streamflow volume forecasts. In terms of forecast skill, all three bias-correction methods performed well for monthly volume forecasts. The analysis found that both the regression and the quantile mapping methods employed produced similar results, except for low flows, where the regression method performed poorly due to its model fit. The forecast skill for the event bias correction method is similar to the others, but the sharpness and discrimination of the probabilistic forecasts are less.

Mehrotra and Sharma (2006) used a non-parametric stochastic downscaling framework to simulate daily rainfall at multiple point locations in catchment-scale to evaluate the climate change impact under enhanced greenhouse conditions.

Busuioc (2007) investigated optimum statistical downscaling models for three winter precipitation indices in the Emilia-Romagna region, especially related to extreme events. The statistical downscaling model (SDM) based on the canonical correlation analysis (CCA) was used as the downscaling procedure. The combination of dynamic and thermodynamic predictors improved the SDM's skill for all sub-regions in the dry index case and for some sub-regions in the simple daily intensity index case. The selected SDMs were stable in time only in terms of the correlation coefficient for all sub-regions for which they were skilful and only for some sub-regions in terms of explained variance.

Fowler (2007) pointed out that since many of the impacts of climate change will not be detectable in the near future, there is a need for decision-making tools for planning and management that are robust in relation to future uncertainties. In hydrological impacts research there is a need for a move away from comparison studies into the provision of such tools based on the selection of robust, possibly impact specific, downscaling methods. These allow the inclusion of uncertainty estimates using a multi-model approach which can be used in the planning of adaptation measures, and they seem to offer the most potential for advancement within both the “downscaling for hydrological impacts” science community and for practitioners.

Graham et al. (2007) investigated how using different regional climate model (RCM) simulations affected the climate change impacts on hydrology in northern Europe using an offline hydrological model. The results indicated an overall increase in river flow, earlier spring peak flows and an increase in hydropower potential. The two approaches for transferring the signal of climate change to the hydrological impacts model yielded similar mean results, but considerably different seasonal dynamics, a result that is highly relevant for other types of climate change impacts studies.

Sharma (2007) employed bias-correction and spatial disaggregation methods to improve the quality of ECHAM4/OPYC SRES A2 and B2 precipitation for the Ping River Basin in Thailand. The bias-correction method, based on gamma-gamma transformation, was applied to improve the frequency and amount of raw GCM precipitation at the grid nodes. The spatial disaggregation model based on the multiplicative random cascade theory was estimated using Mandelbrot-Kahane-Peyriere (MKP) function for each month. The bias-correction method showed the ability of reducing biases from the frequency and amount compared observed rainfall data. The spatial disaggregation model satisfactorily reproduces the observed trend and variation of average rainfall amount except during heavy rainfall events with certain degree of spatial and temporal variations.

Cavazos and Hewitson (2008) examined the skill and errors of 29 individual atmospheric predictors of area-averaged daily precipitation in 15 locations that encompass a wide variety of climate regimes, and to determine the best combination of these to empirically model daily precipitation during the winter and summer seasons. The results indicate that humidity and geopotential heights at mid-tropospheric levels are the two most relevant controls of daily precipitation in all the locations

Cheng et al. (2008) used a regression-based methodology to downscale hourly and daily station-scale meteorological variables from outputs of large-scale general circulation models (GCMs). The results showed that the downscaling method was able to capture the relationship between the premises and the response.

Ghosh and Mujumdar (2008) proposed the methodology for statistical downscaling based on sparse Bayesian learning and Relevance Vector Machine (RVM) using GCM simulated climatic variables. NCEP/NCAR reanalysis data have been used for training the model to establish a statistical relationship between streamflow and climatic variables. The relationship thus obtained is used to project the future streamflow from GCM simulations. A decreasing trend was observed for the monsoon streamflow of Mahanadi due to high surface warming in the future, with the CCSR/NIES GCM and B2 scenario.

Piani et.al. (2009) produced internally consistent fields that had the same statistical intensity distribution as the observations. They referred to this as a statistical bias correction. Validation of this methodology was carried out using daily precipitation fields, defined in relation to Europe, from the ENSEMBLES climate model dataset. The results showed that this method performed unexpectedly well in both intensity distribution and a drought and heavy precipitation indication.

Wetterhall et al. (2009) adopted a multi-objective fuzzy-rule-based classification method (MOFRBC) to downscale GCM daily precipitation at the station level. The predictor data included mean sea level pressure (MSLP) and geopotential heights at 850 (H850) and 700 hPa (H700) from the NCEP/NCAR reanalysis and from the HadAM3 GCM.

Sperna Weiland (2010) investigated the capability of GCMs data for discharge variability and extremes analysis. This study used the bias-corrected daily climate data from 12 GCMs as input data to the global hydrological model PCR-GLOBWB. The results were compared with discharge observations of the GRDC and the discharges calculated from the model runs based on two meteorological datasets constructed from the observation-based CRU TS2.1 and ERA-40 reanalysis. The consistency of bias-corrected GCM data revealed that was high for mean discharge and timing (Qpeak), but relatively low for inter-annual variability (IAV). It was implied that GCMs can be of use in global hydrological impact studies in which persistence is of less relevance (e.g. in the case of flood rather than drought studies). Moreover, the bias-correction influences mean discharges more than extremes, which has a positive consequence that changes in daily rainfall distribution and subsequent changes in discharge extremes will also be preserved when the bias-correction method is applied to future GCM datasets.

Koontanakulvong and Chaowiwat (2010) reviewed and verified the performance of MRI GCM data with respect to Thailand conditions. This study compared the performance of the bias correction method for projecting the climate change in the future in 9 group basins of Thailand. The bias correction methods included the SD ratio method and the modified rescaling method. The monthly mean rainfall distribution pattern by SD Ratio-GCM was found to be closer to the observed rainfall. The results of SD Ratio GCM incorporated the spatial heterogeneity in rainfall and reduced the biases from raw GCM in terms of monthly mean and distribution rainfall patterns.

Inomata et al. (2011) developed a simple statistical method to correct bias in the MRI GCM20 precipitation data. The method primarily aimed to correct the intensity of the GCM20 daily precipitation samples to express both seasonal patterns and extreme values appropriately. The basic idea of the bias correction was to adjust the probability distribution of GCM20 daily precipitation to that of its observed counterparts. The results showed that it appropriately corrected the GCM20 bias in both monthly and extreme daily precipitation.

Watanabe et al. (2012) evaluated the bias-correction methods for monthly temperature and precipitation data simulated by 12 GCMs in the Coupled Model Intercomparison Project (CMIP3) archives. They proposed a new method which conserved the changes of mean and standard deviation of the uncorrected GCM data, and then compared with five previous bias-correction methods. They found that new method successfully conserved the changes in the mean, standard deviation and the coefficient of variation before and after bias-correction. The differences of bias-corrected data among methods were discussed according to their respective characteristics.

From the reviewed bias correction method, this study selected four statistical bias correction methods in order to compare the performance of each method. The selected bias correction methods include Gamma-gamma (GG) transformation, the Hybrid method, the standard deviation ratio method and the modified rescaling method. Thus, these bias correction methods are widely used to assess the impact on hydrological process and their results can represent the regional hydrological characteristics. Especially, the hybrid method has been proposed to correct the MRI GCM bias appropriately for both monthly and extreme daily precipitation.

3.3 Rainfall-runoff estimation

Many researchers have applied some technique to estimate the runoff parameters from the characteristics of river basins such the land use and soil group maps. While those studies considered the runoff parameters which based on the characteristics of the river basin only. However, the runoff parameter estimation studies based on the storm pattern have been very few. Many researchers have studied the rainfall-runoff models as follows:

Uhlenbrook (1999) investigated the uncertainties arising from the problem of identifying a representative model structure and model parameters in a conceptual rainfall-runoff model. They applied this model to calculate the design flood and predict the low flow. The results showed that the parameter uncertainty and the uncertainty of identifying a unique best model variant have implications for model predictions.

Hernandez et al. (2000) described a procedure for evaluating the effects of land cover change and rainfall spatial variability on watershed response. Two hydrologic models were applied in this research on a small semi-arid watershed; one model is event-based with a one-minute time step (KINEROS), and the second one was a continuous model with a daily time step (SWAT). This study demonstrated the feasibility of using widely available data sets for parameterizing hydrologic simulation models. The results showed that both models were able to characterize the runoff response of the watershed due to changes of land cover.

Wilk and Hughes (2002) simulated streamflow in a regulated catchment in southern India by using a rainfall-runoff model, where data were limited in relation to the basin's complexity. The results showed that the proposed model could be considered a useful water resources management tool that provides a sound basis for further studies.

Pappenberger et al. (2004) investigated the uncertainty of the GIS based rainfall runoff model (LisFlood) by using the Generalized Likelihood Uncertainty Estimation (GLUE) framework. The results of the prediction of uncertainty percentiles regarding the flow in this research were very satisfactory and encouraging. The analysis showed the capability of the proposed model in predicting the uncertainty for estimating the exceedence of threshold levels, which can be used in flood warning decision making and river basin management.

Maskey et al. (2004) presented a methodology for propagating the precipitation uncertainty through a deterministic rainfall-runoff-routing model for flood forecasting. It uses fuzzy set theory combined with genetic algorithms. The uncertainty due to the unknown temporal distribution of the precipitation was achieved by disaggregation of the precipitation into sub-periods. A catchment model of the Klodzko valley (Poland) built with HEC-1 and HEC-HMS was used for the application. The results showed that the output uncertainty due to the uncertain temporal distribution of precipitation could be significantly dominant over the uncertainty due to the uncertain quantity of the precipitation.

Murphy et al. (2004) have stated that the application of a lumped conceptual rainfall-runoff model for simulating beyond a baseline calibration set was a major challenge for climate change impact assessment. They applied the HYSIM as an “off-the-shelf” conceptual rainfall runoff model using data on a daily time-step to a suite of catchments throughout Ireland. A number of acceptable parameter sets were generated and uncertainty bounds were constructed for each time step using the 5th and 95th percentile at each temporal interval.

Pappenberger and Beven (2005) have stated that an understanding of cascaded uncertainties is a necessary requirement to provide robust predictions. Their analysis demonstrates that a full uncertainty analysis of such an integrated system is limited mainly by computer power as well as by how well the rainfall predictions represent potential future conditions.

Magome et al. (2008) discussed the approach of using a currently available distributed hydrological model to couple with satellite-based precipitation datasets. A physically based distributed hydrological model, the YHyM/BTOP model, was used in this paper to simulate at any grid for the whole Mekong River Basin, including poorly gauged basins. The results showed the simulated discharge could represent the trend of observed discharge and the possibility of real-time flood risk assessment well.

Sugiura et al. (2009) developed a concise flood-run-off analysis system as a toolkit for more effective and efficient flood forecasting in developing countries. This system implemented interfaces to input not only ground-based but satellite-based rainfall data, GIS functions to construct flood-run-off models, a default run-off analysis model, and interfaces to display output results.

3.4 Decision making analysis for water management

There are many researches that have applied some decision-making techniques to study water management, such as the risk-based decision analysis and the systematic decision analysis, etc. Recently, the decision-tree algorithm was applied to reservoir releases during typhoons. Some decision-making researches for water management are reviewed below.

Mylopoulos et.al. (1999) proposed a risk-based decision analysis methodology that could be used as a water policy tool in the design of economic incentive instruments under conditions of uncertainty.

Al-Faqih et al. (2006) proposed a systematic decision analysis tool to provide strategies for finding sustainable water resources and drainage systems solutions. A new sustainable decision analysis system was developed to address these problems and concerns. The developed system was very flexible and could be modified according to the project. Stakeholders will gain a comprehensive outlook for the water and/or drainage system problems under consideration.

Harvey et. al. (2009) introduced the concept of quantitative decision analysis as the logical extension of the recent implementation of risk analysis in flood risk management. The conceptual framework defined five layers of analysis included the damage simulation, risk analysis, management intervention and performance assessment.

Chih-Chiang et. al. (2012) compared the decision-tree algorithm (C4.5) the neural decision-tree algorithm (NDT) to solve the problem of water resources management. The feature of the NDT algorithm was the combination of the artificial neural network (ANN) technologies and the conventional decision-tree algorithm capabilities. The applicability of the presented algorithms is demonstrated through a case study of reservoir releases during typhoons. Shihmen Reservoir in Taiwan is the study site. The findings show superior performance of the NDT model in contrast to the traditional C4.5.

3.5 Reservoir operation

Reservoir operations consist of the storage and release of reservoir for multiple-purposes. The reservoir regulators determine the water managing plan in each period and carry out according to this plan. If the future condition occurs different from the plan, the operation may be adjusted from the plan for reducing deficit and overflow.

There are many reservoir operation approaches that can assist reservoir operators in releasing or storing water in reservoirs; namely, stochastic dynamic programming model, probability-based rule curves and genetic algorithm, etc. Regarding to the reservoir operation approaches were applied to find the suitable rule curves, and these rule curves will be used for the operating guide line. Furthermore, the rule curve is used to refer to elevations which define ideal (desirable or target) storage volumes and provide a mechanism for release rules to be specified as a function of storage content. Many researchers have studied the impact of climate change on reservoir operation; however, there were a few researches has investigated the adaptive reservoir operation response to such an impact. The reservoir operation approaches and reservoir operation under climate change condition are reviewed as follows.

3.5.1 Reservoir operation approaches

Harboe and Ratnayake (1993) proposed the standard operating rules by using a stochastic dynamic programming model. The objective function was to maximize expected guaranteed on-peak energy while constraints on irrigation and flood control were satisfied. The results showed that stochastic results were more conservative (lower energy targets), but in turn had a higher reliability than higher targets obtained from deterministic models.

Jiang (1998) applied the Wiener process characteristics of reservoir storage capacity in flood regulation by using a stochastic differential equation. The results showed that the uncertainty influence of various random factors on the reservoir level hydrograph could be taken into account in the flood routing process.

Vonnarart (2003) developed the reservoir operation rule by using ANN. The results showed that the ANN model could reduce the overflow amount in moderate runoff case but rarely reduced overflow in high runoff case. The ANN model could not improve reservoir operations during dry season. The developed ANN model in wet season could assist daily operation in relation to moderate runoff conditions.

Vudhivanich and Rittima (2003) developed the probability based rule curves were developed for Mun Bon and Lam Chae reservoirs, Nakhon Ratchasima province. The effectiveness of this approach could be evaluated by comparing the results with the standard operating policy. The results showed that the failure indices in terms of the number of months, sum and sum squared of the water shortage of the probability based rule curves were smaller than those of the standard operating policy.

Hanasaki et. al. (2003) studied a simple reservoir operation model for Total Runoff Integrating Pathways (TRIP), which is one of the global river routing network models. The model was applied to the Chao Phraya River in Thailand to validate its performance. The results showed the good correspondence between the model results and observations for applying the model to global and continental studies.

Chaleeraktrakoon and Kangrang (2005) formulated a multi-staged problem of rule-curve searching using the DP technique, and proposed the PPO algorithm for finding the optimal rule curves of the reservoir system. The proposed DP/PPO approach has been applied to determine the optimal rule curves of the Bhumibhol and Sirikit Reservoirs (the Chao Phraya River Basin, Thailand). It was shown in the illustrative application that the proposed approach consumed computing resources that were much fewer than the DP problem did. The results indicated that the proposed DP-based approach is advantageous over the accepted simulation practice since it certainly provides the optimal rule curves.

Kumar et.al. (2006) proposed a genetic algorithm GA model for obtaining an optimal operating policy and optimal crop water allocations from an irrigation reservoir. The objective is to maximize the sum of the relative yields from all crops in the irrigated area. This model can be used to optimize the water utilization of any reservoir system to achieve maximum benefits.

Ratnayake and Harboe (2007) used the Stochastic Dynamic Programming and Deterministic Dynamic Programming techniques to optimize a reservoir system under a max-min type of objective function to maximize on-peak firm energy generation. The result showed that the SDP was not appropriate for the optimization as it significantly overestimates the firm energy targets while the DDP resulted in very reasonable on-peak firm energy targets. The simulation results showed high reliabilities for targets from DDP while those from SDP are very low.

Kangrang et. al. (2008) developed a stochastic simulation model embedded genetic algorithm model for searching the optimal rule curves. The synthetic inflows were used in the developed model for assessing the risk reservoir operation. Single and multi-reservoir systems were applied to assess the efficiency of the proposed technique. The developed model was applied to determine the optimal rule curves of the Bhumibol and Sirikit Reservoirs (the Chao Phraya River Basin, Thailand) for multi-reservoir system and the Ubolratana Reservoir (the Chi River Basin, Thailand) for single system. The optimal rule curves of each system were used for assessment using a Monte Carlo simulation. The results showed that the situations of water shortage and excess release of the obtained rule curves were not significantly different from the situation of the curves searched using traditional simulation.

Soltani et. al. (2008) applied the optimization of reservoir operation rules by using differential evolutionary algorithm with stochastic inflow scenarios. The results showed the uncertainty band of inflow which is narrowed in demand which supplies through optimal reservoir operation planning.

Pinthong et. al. (2009) developed a hybrid genetic and neurofuzzy computing algorithm to enhance the efficiency of water management for a multipurpose reservoir system. The genetic algorithm was applied to search for the optimal input combination of a neurofuzzy system. The optimal reservoir releases were determined based on the reservoir inflow, storage stage, side flow, diversion flow from the adjoining basin, and the water demand.

Celeste et al. (2009) incorporated the application of Implicit Stochastic Optimization (ISO) to determine monthly operating rules for a reservoir system with new inflow realizations. The results showed ability to produce policies similar to those obtained by deterministic optimization taking the same inflows as perfect forecasts.

Celeste and Billib (2009) investigated the performance of seven stochastic models used to define optimal reservoir operating policies. The models were based on implicit (ISO) and explicit stochastic optimization (ESO) as well as on the parameterization–simulation–optimization (PSO) approach. The models were applied to the operation of a single reservoir damming at an intermittent river in northeastern Brazil. The standard operating policy was used to compare with the proposed approach. The results showed that the ISO and PSO models performed better than the SDP and the SOP. In addition, the proposed ISO-based surface modeling procedure and the PSO-based two-dimensional hedging rule provided superior overall performance as compared with the neuro-fuzzy approach.

Rittima (2009) simulated reservoir operation by using a hedging policy that was applied at the Mun Bon and Lam Chae reservoirs. The results were compared with the standard operating policy and probability based rule curve. The results showed that two-point and three-point hedging performed well for all components of reservoir behavior compared with the standard operating policy and other hedging policies.

3.5.2 Reservoir operation under climate change condition

Kaczmarek (1990) studied the possible impacts of long-term hydrological nonstationarity on the design and operation of water reservoir systems. Stochastic storage theory was used to derive the relationship between annual storage capacity, water demand and various performance criteria of reservoir management. This was applied to a set of scenarios, and it was shown that despite moderate changes in inflow stochastic characteristics, the values of the performance criteria were substantially different.

Burn and Simonovic (1996) studied the potential impacts of climate change on the operational performance of the Shellmouth reservoir in Manitoba, Canada. They applied two different “warm” and “cool” sets of climatic conditions and synthesized monthly streamflow sequences as input data for a reservoir operation model. They also assessed the impact of the reliability of reservoir operating policy included flood control, recreation and water supply. The reservoir performance was determined to be sensitive to the inflow data.

Kim et al. (2009) evaluated the current dam operation rules of Yagisawa Dam under the changed climate conditions. They applied the object oriented hydrologic modeling system and the dam operation model to simulate the water level and outflow with the present and future inflow. The results results showed that there was very limited inflow in May and June due to decreased and shifted snowmelt inflow in the future. The dam outflow from January to March should be reduced and stored in the reservoir, or the current water level regulations should be revised.

Brekke (2009) presented a flexible methodology for conducting climate change risk assessments involving reservoir operations. The multiple applications were conducted to show how choices made in conducting the risk assessment, choices known as analytical design decisions, can affect assessed risk. The results show that assessed risk would motivate different planning pathways depending on decision-maker attitudes toward risk (e.g., risk neutral versus risk averse). Furthermore, the results also show that assessed risk at a given risk attitude is sensitive to the analytical design choices listed above, with the choice of whether to adjust flood-control rules under climate change having considerably more influence than the choice on whether to weight climate scenarios.

Lauri, et.al. (2012) downscaled the output of five general circulation models (GCMs) and applied the simulation of reservoir operation by using an optimization approach considering both existing and planned hydropower reservoirs in the Mekong region. They also applied a distributed hydrological model for the hydrological assessment. Their results showed that within the coming 20–30 years, the operation of planned hydropower reservoirs was likely to have a larger impact on the Mekong hydrograph than the impacts of climate change, particularly during the dry season. On the other hand, climate change will increase the uncertainty of the estimated reservoir operation impacts.

3.5.3 Adaptive reservoir operation

Kim et al. (2009) investigated the adaptability of current dam reservoir operation rules under climate change condition in the upper part of Tokyo, Japan. Regarding to the inflow data under the present and future climate condition, hydrologic output of a general circulation model was converted into discharge data through a distributed hydrologic model. The simulation results showed that there will be very limited inflow in May and June due to decreased and shifted snowmelt inflow in the future. Under the changed climate conditions, the dam outflow from January to March should be reduced and stored in the reservoir, or the current water level regulations should be revised.

Georgakakos et al. (2012) assessed the value of adaptive reservoir management compare with traditional operation practices in the context of climate change for the Northern California reservoir system. They compared the water system response in four simulated scenarios, pertaining to two management policies and two hydrologic data sets. The results showed that the current policy which was tuned to historical hydrologic regimes, was unable to cope effectively with the more variable future climate, and that the system has higher vulnerabilities and risks. By contrast, adaptive management constitutes an effective mitigation measure of climate change.

CHAPTER IV
STUDY THEORIES AND PROCEDURES

4.1 Bias correction of GCM rainfall and change on hydrological variables

The bias correction of GCM rainfall includes the GCM selection and the comparative study of bias correction method which is the pre-process of the impact assessment on climate change on the local scale. For the change on hydrological variables is to evaluate the trend of change of the input variables for the reservoir operation model. The schematic diagram of bias correction of GCM rainfall procedures and the impact assessment on hydrological variables procedures show as Figure 4.1 and 4.2.

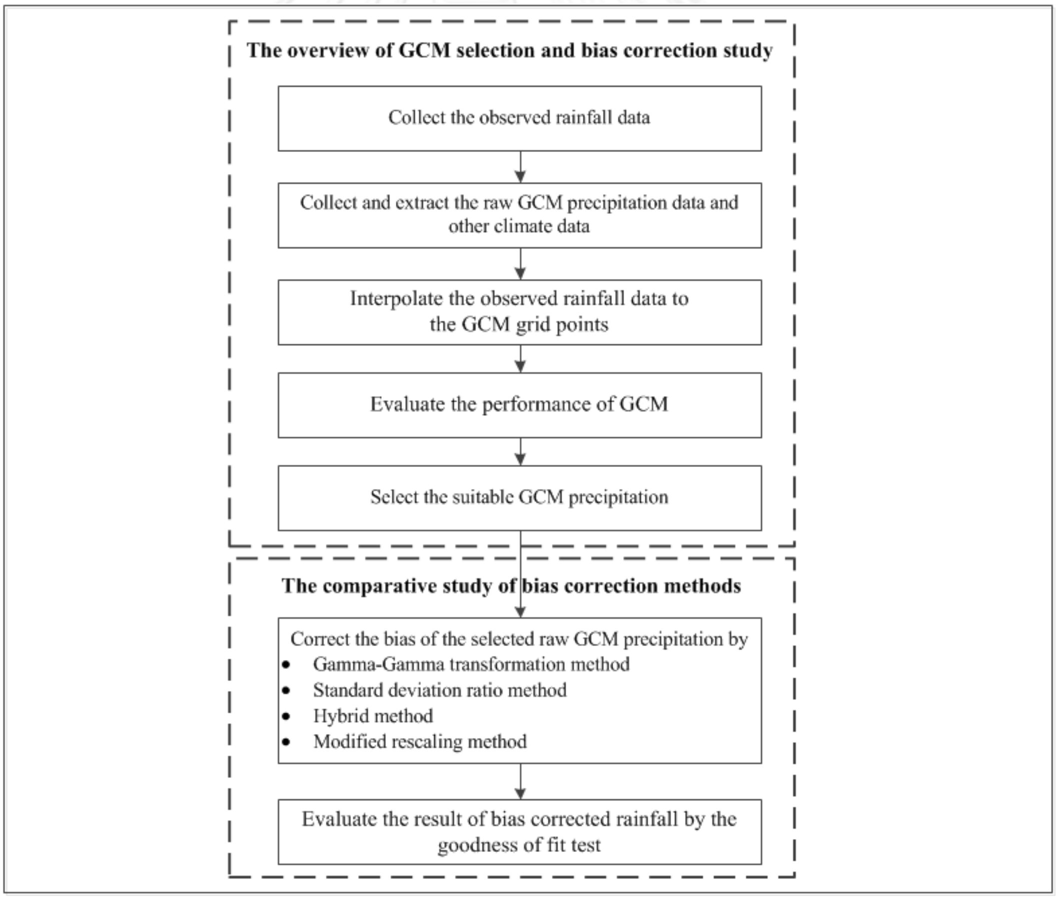


Figure 4.1 Schematic diagram procedures of bias correction of GCM rainfall

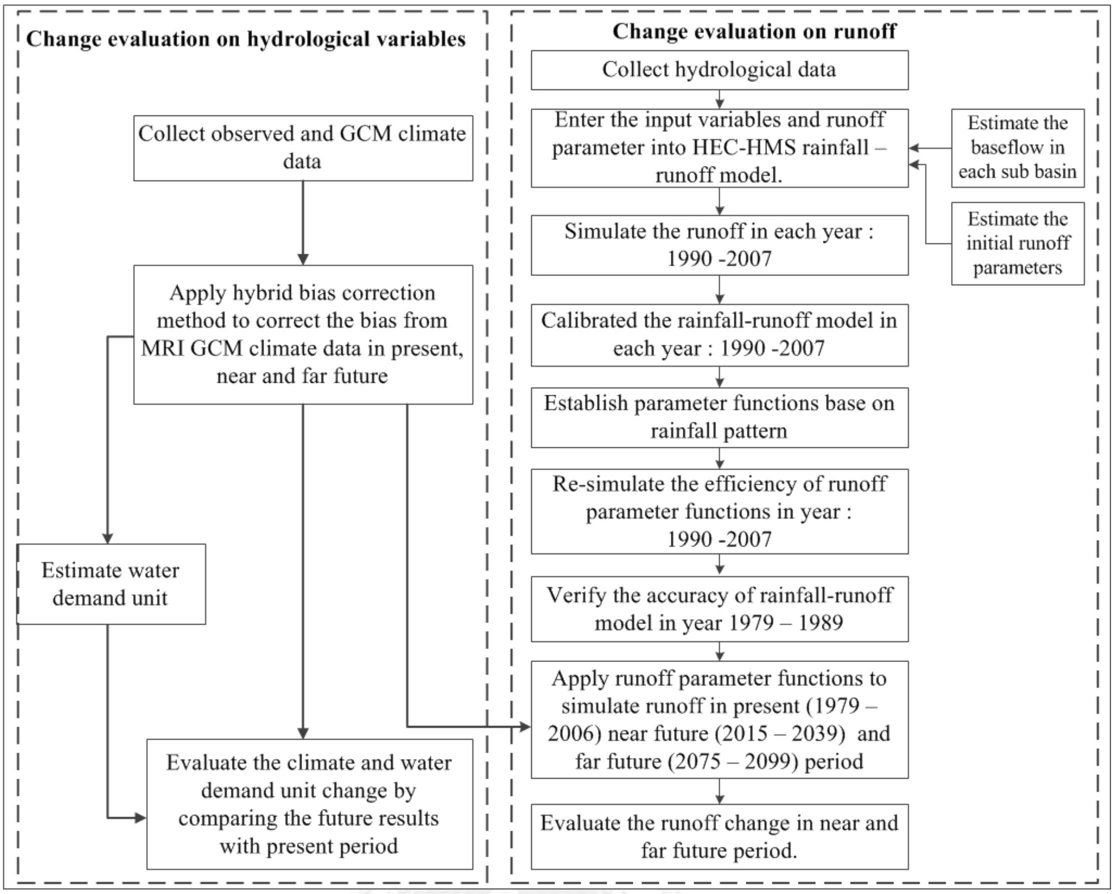


Figure 4.2 The change evaluation procedures on hydrological variables

The detail of the bias correction of GCM rainfall and change on hydrological variables follow as:

4.1.1 GCM selection

4.1.1.1 Data Collection for the GCM selection

The General Circulation Model (GCM) climate data was collected from many related agencies by extracting from the web site of the distributing agencies e.g. CCSR, CSIRO, Max Planck Institute for Meteorology, GFDL, Hadley Centre, CCCMA. For the MRI GCM climate data was extracting from Meteorological Research Institute, Japan. The list of collecting data was shown as Table 4.1.

4.1.1.2 The GCM selection procedures

The GCM selection is to evaluate the performance of GCM climate data that has the reliability for applying the hydrological model. The GCM selection procedures follow as:

1) Collect the observed rainfall data from Thai Meteorological Department (TMD) and Royal Irrigation Department (RID).

2) Collect GCM precipitation data from the IPCC data distribution center Meteorological Research Institute Japan.

3) Extract and select GCM climate data series from grid database which matches the study area.

4) Interpolate the observed rainfall data to the GCM grid points by the inverse distance weighting method.

5) Evaluate the performance of GCM by using the goodness of fit test indices based on monthly basis.

6) Select the suitable GCM precipitation by comparing the performances of raw GCM precipitation.

Table 4.1 List of climate data collection

Data[2/]	Scenario[1/]	Agency	Time scale	Duration
Observed climate	-	Thai Meteorological Department (TMD) and Royal Irrigation Department	Daily, Monthly	1979 - 2006
CCSR-A2 climate	A2	Center for Climate system Research, USA	Monthly	1979 - 2006
CSIRO-A2 climate	A2	Commonwealth Scientific and Industrial Research Organization, Australia	Monthly	1979 - 2006
ECHAM4-A2 climate	A2	Max Planck Institute for Meteorology, Germany	Monthly	1990 - 2006
GFDL-A2 climate	A2	The Geophysical Fluid Dynamics Laboratory, USA	Monthly	1979 - 2006
HadCM3-A2 climate	A2	Hadley Centre, the United Kingdom	Monthly	1979 - 2006
CCCma3-A2 climate	A2	The Canadian Centre for Climate Modeling and Analysis, Canada	Monthly	1979 - 2006
MRI-A2 climate	A2	Meteorological Research Institute, Japan	Daily, Monthly	1979 - 2006
CCSR-B2 climate	B2	Center for Climate system Research, USA	Monthly	1979 - 2006
CSIRO-B2 climate	B2	Commonwealth Scientific and Industrial Research Organization, Australia	Monthly	1979 - 2006
ECHAM4-B2 climate	B2	Max Planck Institute for Meteorology, Germany	Monthly	1990 - 2006
GFDL-B2 climate	B2	The Geophysical Fluid Dynamics Laboratory, USA	Monthly	1979 - 2006
HadCM3-B2 climate	B2	Hadley Centre, the United Kingdom	Monthly	1979 - 2006
CCCma3-B2 climate	B2	The Canadian Centre for Climate Modelling and Analysis, Canada	Monthly	1979 - 2006
MRI-B2 climate	B2	Meteorological Research Institute, Japan	Daily, Monthly	1979 - 2006
CCSR-A1B climate	A1B	Center for Climate system Research, USA	Monthly	1979 - 2006
CSIRO-A1B climate	A1B	Commonwealth Scientific and Industrial Research Organization, Australia	Monthly	1979 - 2006
ECHAM4-A1B climate	A1B	Max Planck Institute for Meteorology, Germany	Monthly	1990 - 2006
GFDL-A1B climate	A1B	The Geophysical Fluid Dynamics Laboratory, USA	Monthly	1979 - 2006
HadCM3-A1B climate	A1B	Hadley Centre, the United Kingdom	Monthly	1979 - 2006
CCCma3-A1B climate	A1B	The Canadian Centre for Climate Modelling and Analysis, Canada	Monthly	1979 - 2006
MRI-A1B climate	A1B	Meteorological Research Institute, Japan	Daily, Monthly	1979 - 2006

Remark 1/ Scenarios were explained more details in appendices B.

2/ Climate data included precipitation, maximum, minimum and mean temperature, and relative humidity

4.1.2 The bias correction of GCM rainfall

The statistical bias correction methods, used in this thesis, included Gamma-gamma (GG) transformation (Ines and Hansen, 2006; Piani et al., 2009), Hybrid bias correction (Inomata et al., 2011), standard deviation (SD) ratio bias correction (Cheng et al., 2007) and modified rescaling bias correction (Graham et al.,2007; Sperna Weiland et al., 2010). These bias correction methods are widely used in the impact assessment on hydrological process and represented the regional climate characteristics.

4.1.2.1 Data collection for bias correction of GCM

The observed climate data was collect from Thai Meteorological Department (TMD) and Royal Irrigation Department (RID). The rainfall gauge stations were used for this study included 64 stations located in Nan River Basin. (shown as Figure 2.2) For the General Circulation Model (GCM) climate data was collected from many related agencies by extracting from MRI. The list of collecting data was shown as Table 4.2.

Table 4.2 List of climate data collection for bias correction of GCM

Data	Scenario[1/]	Agency	Time scale	Duration
Observed rainfall	-	Thai Meteorological Department and Royal Irrigation Department	Daily, Monthly	1979 - 2006
Observed maximum temperature	-	Thai Meteorological Department	Daily, Monthly	1979 - 2006
Observed minimum temperature	-	Thai Meteorological Department	Daily, Monthly	1979 - 2006
Observed mean temperature	-	Thai Meteorological Department	Daily, Monthly	1979 - 2006
Observed relative humidity	-	Thai Meteorological Department	Daily, Monthly	1979 - 2006
MRI-A1B precipitation	A1B	Meteorological Research Institute, Japan	Daily, Monthly	1979 - 2006
MRI-A1B maximum temperature	A1B	Meteorological Research Institute, Japan	Daily, Monthly	1979 - 2006
MRI-A1B minimum temperature	A1B	Meteorological Research Institute, Japan	Daily, Monthly	1979 - 2006
MRI-A1B mean temperature	A1B	Meteorological Research Institute, Japan	Daily, Monthly	1979 - 2006
MRI-A1B relative humidity	A1B	Meteorological Research Institute, Japan	Daily, Monthly	1979 - 2006

Remark 1/ Scenarios were explained more details in appendices B.

4.1.2.2 The comparative study of bias correction methods

4.1.2.2.1 Gamma-gamma (GG) transformation procedures

The Gamma-gamma (GG) transformation procedure was modified from Ines (Ines, 2006). The detail of procedures followed as:

1) Correct the empirical distribution probability of observed daily rainfall data (CDFobs), the threshold or minimum rainfall value was defined as 0.1. Thus, the observed rainfall values under 0.1 would be truncated.

2) Calculate the alpha and beta parameter in each month in observed rainfall data by using maximum likelihood method. Thus, the alpha (α) and beta (β) parameter was calculated from this equation as (Law and Kelton, 1982):

$$?? = \left(\frac{??}{??}\right)^2 \tag{1}$$

$$?? = \frac{??^2}{??} \tag{2}$$

where μ is the daily mean rainfall in each month.

β is the daily standard deviation rainfall in each month.

3) Calculate the alpha (α) and beta (β) parameter in each months in raw GCM rainfall data by using maximum likelihood method as Eq.1 and 2.

4) Correct the empirical distribution probability of raw GCM data (CDFgcm), the threshold or minimum rainfall value was defined as 0.1. Thus, the raw GCM rainfall values under 0.1would be truncated.

5) Map the GCM rainfall data onto the probability of observed rainfall data (CDFobs).

6) Correct the gamma distribution of mapping GCM rainfall (CDFgcm') by using alpha and beta parameter from step 3. Thus, the alpha and beta parameter were calculated from GCM rainfall data.

7) Transform the CDFgcm' to the bias corrected GCM rainfall data by inversing the gamma probability of CDFgcm' from step 6. Hence, the alpha and beta parameter were calculated from observed rainfall data. For GG transformation, the truncated daily GCM rainfall and historical rainfall data are fitted to a two-parameter gamma distribution (Eq. 1) and then the cumulative distribution (Eq. 2) of the truncated daily GCM rainfall is mapped to the cumulative distribution of the truncated historical data (Eq. 3). The shape and scale parameters (α and β) for each gamma distribution are determined using Maximum Likelihood Estimation.

$$f(x\colon \alpha,\beta) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} exp\left(-\frac{x}{\beta}\right) \; ; \quad x \geq x_{Trunc} \tag{3}$$

$$F(x;\, \alpha,\beta) = \int_{x_{Trunc}}^{x} f(t)dt \tag{4}$$

$$F(x_{GCM};\, \alpha,\beta|_{GCM}) \Rightarrow F(x_{His};\, \alpha,\beta|_{His}) \tag{5}$$

The corrected GCM rainfall amount for the particular day can be calculated by taking the inverse of Eq. (3) such that:

$$x'_{GCM} = F^{-1}\{F(x_{His};\, \alpha,\beta|_{His})\} \tag{6}$$

8) Evaluate the result of bias corrected rainfall by the goodness of fit test.

4.1.2.2.2 Standard deviation ratio bias correction procedures

1) Generate the monthly rainfall map for verifying data by using the inverse distance weighted interpolation method.

2) Correct the bias of MRI GCMs precipitation data follow these equations. The bias correcting technique, used in this study, was developed by Cheng et.al. (2007) by using the following expression:

$$P_{his-new} = (P_{his-old} - \overline{P}_{his-old})\frac{S_O}{S_{his-old}} + \overline{O} \tag{7}$$

where $P_{his-new}$ and $\overline{P}_{his-old}$ are predictions of monthly bias correcting transfer functions for a GCM historical run after and before correction. S_O and $S_{his\text{-}old}$ are standard deviations of observations and model predictions for the historical run, respectively. $P_{his\text{-}old}$ and $\bar{O}$ are overall averages of model predictions and observations.

3) Evaluate the result of bias corrected rainfall by the goodness of fit test.

4.1.2.2.3 Hybrid bias correction procedures

The Hybrid Bias Correction Method was developed from International Centre for Water Hazard and Risk Management. (Kazuhiko and Hironori, 2009; Inomata et al., 2011). The approach can be concluded as follow:

1) Generate probability density function (pdf) from MRI GCM rainfall data and observed data on daily basis in year 1979 – 2006.

2) Separate MRI GCM rainfall data and observed data to 2 part i.e. probability at 99.5% and probability at over top 0.5% (based on comparison study of 99% – 99.9%)

3) Take the data from 2nd Process to Generate probability density function (pdf).

4) Calculate the corrected ratio of each grid cells. For probability 99.5% can be calculated by this equation :

$$\alpha_{q99.5\%} = \frac{P\_Obs_{q99.5\%}}{GCM\_Pr\,e_{q99.5\%}} \tag{8}$$

where $\alpha_{q99.5\%}$ is the correction ratio at probability 99.5%; $P\_Obs_{q99.5\%}$ is the observed rainfall at probability 99.5%; $GCM\_Pre_{q99.5\%}$ is the MRI GCM Rainfall data at probability 99.5%.

5) Take αq values for 4th process to multiply with MRI GCM rainfall data at probability 99.5%

$$P\_Pre_{q99.5\%} = \alpha_{q99.5\%} \times GCM\_Pre_{q99.5\%} \tag{9}$$

where $P\_Pre_{q99.5\%}$ is the bias corrected MRI GCM rainfall at probability 99.5%

6) Find out correction ratio of each grid cells. For probability over top 0.5%can be calculated by this equation :

$$\alpha_{q0.5\%} = \frac{P\_Obs_{q0.5\%}}{GCM\_Pre_{q0.5\%}} \tag{10}$$

where $\alpha_{q0.5\%}$ is the corrected ratio at probability over top 0.5%; $P\_Obs_{q0.5\%}$ is the observed rainfall at probability over top 0.5%; $GCM\_Pre_{q0.5\%}$ is the MRI GCM rainfall at probability over 0.5%.

7) Take α_q values for 6th process to multiply with MRI GCM rainfall data at probability over top 0.5%

$$P\_Pre_{q0.5\%} = \alpha_{q0.5\%} \times GCM\_Pre_{q0.5\%} \tag{11}$$

where $P\_Pre_{q0.5\%}$ is the downscaled MRI GCM rainfall data at probability over top 0.5%

8) Merge the downscaled MRI GCM rainfall data from 5th and 6th together that is the downscaled MRI data in period 1979 – 2006.

9) Evaluate the result of bias corrected rainfall by the goodness of fit test.

4.1.2.2.4 Modified rescaling bias correction procedures

1) Collected and studied observed rainfall in Nan River Basin from Royal Irrigation Department (RID) and Thai Meteorological Department (TMD).

2) Collected MRI GCM precipitation in Nan River Basin from Meteorological Research Institute (MRI, Japan).

3) Correct the bias of the MRI GCMs precipitation data follow these equations:

$$\alpha = \frac{R_{obs}}{R_{mri}} \tag{12}$$

4) Minimize the root mean square error from this equation:

$$RMSE = \sqrt{\frac{1}{n}\sum_{j=1}^{n}\left(R_{obs} - R_{mri}\right)^2} \tag{13}$$

where α is the bias Correction factors in each grids; R_{obs} is the monthly mean observed rainfall, mm/month; R_{mri} is the monthly mean MRI rainfall, mm/month.

5) Calculate the bias corrected rainfall follow this equation:

$$R_{bias} = \alpha * R_{mri}$$

where α is the bias corrected factors in each grid; R_{mri} is the monthly mean MRI rainfall, mm/month.

6) Evaluate the result of bias corrected rainfall by the goodness of fit test.

4.1.3 The change on hydrological variables

The hydrological variables in this study include three groups of variables such as the climate group, the water demand rate group and runoff group. The detail of change evaluation procedures follow as:

4.1.3.1 Data collection for the change on hydrological variables

The data collection for hydrological variables included the observed and GCM climate data such rainfall, temperature, relative humidity and runoff etc. shown as Table 4.3. Furthermore the future bias corrected rainfall would be used to apply with the future period. For the runoff group includes observed rainfall, observed runoff, characteristic of sub basin and land use map. For the observed data was collected in year 1979 – 2011, the GCM climate data was collected in near future (year 2015 – 2039) and far future (year 2075 – 2099), respectively.

4.1.3.2 The change evaluation on climate and water demand rate procedures

1) Collect the observed climate data (year 1979 – 2006) included rainfall, maximum, minimum and mean temperature, relative humidity, solar radiation, wind speed and sunshine duration.

2) Collect the present (year 1979 – 2006) and future MRI GCM climate data (year 2015 – 2039 and 2075 – 2099) included rainfall, maximum, minimum and mean temperature, relative humidity.

3) Follow the hybrid bias correction method for correcting the bias of climate data in the present period and find out the corrected ratio. And then correct the bias of future GCM climate data (year 2015 – 2039 and 2075 – 2099) by using $\alpha_{q99.5\%}$ correction factor from Eq.(6) and $\alpha_{q0.5\%}$ correction factor from Eq.(8) multiply with future MRI GCM climate data as this equation:

$$P\_Fu_{q99.5\%} = \alpha_{q99.5\%} \times GCM\_Fu_{q99.5\%} \tag{14}$$

$$P\_Fu_{q0.5\%} = \alpha_{q0.5\%} \times GCM\_Fu_{q0.5\%} \tag{15}$$

where $GCM\_Fu_{q99.5\%}$ is the future MRI GCM climate data at probability 99.5%; $GCM\_Fu_{q0.5\%}$ is the future MRI GCM climate data at probability over top 0.5%; $P\_Fu_{q99.5\%}$ is the bias corrected future MRI GCM climate data at probability 99.5%; and $P\_Fu_{q0.5\%}$ is the bias corrected future MRI GCM climate data at probability over top 0.5%.

Table 4.3 List of data collection for hydrological variables

Data	Agency	Time scales	Duration
a) climate group, water demand unit group			
Observed rainfall	Thai Meteorological Department and Royal Irrigation Department	Daily	1979 - 2011
Observed maximum temperature	Thai Meteorological Department	Daily, Monthly	1979 - 2011
Observed minimum temperature	Thai Meteorological Department	Daily, Monthly	1979 - 2011
Observed mean temperature	Thai Meteorological Department	Daily, Monthly	1979 - 2011
Observed relative humidity	Thai Meteorological Department	Daily, Monthly	1979 - 2011
MRI-A1B precipitation	Meteorological Research Institute, Japan	Daily, Monthly	1979 - 2006, 2015 - 2039, 2075 - 2099
MRI-A1B maximum temperature	Meteorological Research Institute, Japan	Daily, Monthly	1979 - 2006, 2015 - 2039, 2075 - 2099
MRI-A1B minimum temperature	Meteorological Research Institute, Japan	Daily, Monthly	1979 - 2006, 2015 - 2039, 2075 - 2099
MRI-A1B mean temperature	Meteorological Research Institute, Japan	Daily, Monthly	1979 - 2006, 2015 - 2039, 2075 - 2099
MRI-A1B relative humidity	Meteorological Research Institute, Japan	Daily, Monthly	1979 - 2006, 2015 - 2039, 2075 - 2099
Crop consumption coefficient	Royal Irrigation Department		
b) runoff group			
Rainfall station (shape file)	Royal Irrigation Department		
Runoff station (shape file)	Royal Irrigation Department		
Observed rainfall	Thai Meteorological Department and Royal Irrigation Department	Daily	1979 - 2012
Observed runoff	Royal Irrigation Department	Daily	1979 - 2012
Observed inflow	Electricity Generating Authority of Thailand	Daily	1979 - 2012
Charcteristic of sub basin	Royal Irrigation Department		
Land use in year 2009 (shape file)	Land Development Department		

4) Estimate the irrigation water demand in Phitsanulok and Chao Phraya Irrigation Project for present period (year 1979 – 2006) and future period (year 2015 – 2039 and 2075 – 2099) by using the bias corrected GCM climate data. Hence, the cropping pattern in Nan and Lower Chao Phraya were applied to the irrigated area. The irrigation water demand can be estimated from these equations follow as:

$$ET = Kc \times Eto \tag{15}$$

$$W_{ir} = \frac{(ET + P - R_e) \times A}{Eff} \tag{16}$$

where W_{ir} is the irrigation water demand, MCM; ET is water consumption of plant, mm; P is the percolation in paddy field, mm/month, assume 2 mm/day; R_e is the effective rainfall, mm/month; A is the irrigated area, rais, assume 1000 rais; Kc is the crop consumption coefficient; Eto is the reference evapotranspiration, mm/month; and Eff is the efficiency of irrigation system.

For the reference evapotranspiration was calculated by Penman Monteith (Smith, 1992).

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{17}$$

where ET_o is reference evapotranspiration, mm day-1; R_n is net radiation at the crop surface, MJ m^{-2} day^{-1}; G is soil heat flux density, MJ m^{-2} day^{-1}, T is mean air temperature at 2 m height, °C, Δ is slope vapour pressure curve, kPa °C^{-1}, γ is psychrometric constant, kPa °C^{-1}, U_2 is wind speed at 2 m height, m s^{-1}, $(e_s$-$e_a)$ is saturation vapour pressure deficit, kPa.

5) Evaluate the change on climate data and water demand unit by comparing future results with the present period results.

4.1.3.3 The change evaluation on runoff

In the runoff estimate adopted HEC-HMS rainfall-runoff model that produced by the Hydrologic Engineering Centre of US Army Corps of Engineers. This study focused on the runoff parameter estimation based on the rainfall pattern. Thus, this study attempted to find out the relationship between the rainfall pattern and runoff parameters included the initial abstraction (Int), curve number (CN) and storage clark coefficient (Sc). The overview of rainfall-runoff simulation procedures follow as:

1) Collect hydrological data such as such as observed rainfall, observed runoff and inflow of Sirikit Dam.

2) Estimate the initial runoff parameters included the initial abstraction (Int), curve number (CN), storage clark number (Sc), Time of concentration (tc), Storage coefficient (R), Muskingum X value and Muskingum K value.

3) Estimate the baseflow in each sub basin by the relationship equation between the minimum flow and the previous 1 month rainfall.

4) Input the variables and parameter into the HEC-HMS rainfall – runoff model.

5) Simulate the runoff in each year: 1990 -2007.

6) Calibrate the rainfall-runoff model in each year : 1990 -2007 by optimizing the runoff volume/direct runoff parameters, CN, Int and Sc.

7) Estimate parameter functions by setting up the rainfall pattern characteristic and formulating the parameter function from the accumulative rainfall and runoff parameter.

8) Evaluate the efficiency of runoff parameter by re-simulating the runoff by the runoff parameter functions in year 1990 – 2007.

9) Verify the accuracy of rainfall-runoff model and parameter functions by simulating runoff in year 1979 – 1989.

10) Apply runoff parameter functions to simulate runoff by using the bias corrected rainfall in present (1979 – 2006) near future (2015 – 2039) and far future (2075 – 2099) period.

11) Evaluate the monthly runoff change in near future (2015 – 2039) and far future (2075 – 2099) period.

4.2 Impact assessment on the existing reservoir operation

4.2.1 Data collection for the existing reservoir operation

The data collection for adaptive reservoir operation included the hydrological data, the related water demand estimated data and reservoir operation data. Hence, the hydrological data included rainfall and runoff at the observed gauge stations. The characteristic of reservoir included height – volume – area curve, crest of spillway, maximum storage level, normal storage level, dead storage level, existing reservoir rule curve and improving reservoir rule curve that propose by RID (RID, 2012). For the reservoir operation data of Sirikit and Bhumibol dam included the inflow, the release, the water level and the storage that recorded by EGAT. The list of data collection shows as Table 4.4.

Table 4.4 List of data collection for the existing reservoir operation

Data	Agency	Time scales	Period
Observed rainfall	Thai Meteorological Department (TMD) and Royal Irrigation Department (RID)	Daily	1979 - 2012
Observed runoff	Royal Irrigation Department (RID)	Daily	1979 - 2012
Observed inflow	Electricity Generating Authority of Thailand (EGAT)	Daily	1979 - 2012
Reservoir operation data	Electricity Generating Authority of Thailand (EGAT)	Daily/Monthly	1979 - 2012
Reservoir characteristics	Electricity Generating Authority of Thailand (EGAT)		
Water allocation	Royal Irrigation Department (RID)	Monthly	1979 - 2009
Cultivated area	Royal Irrigation Department (RID)	Seasonal	1979 - 2009

4.2.2 Existing reservoir operation modeling

The objective of existing reservoir operation modeling is to assess the impact of climate change on the reservoir water balance via the existing reservoir operations. This study adopted the release – storage ratio method to deal with the reservoir operation based on the storage of reservoir (Hanasaki et. al. 2003). Hence, this study modified the release – storage ratio to formulate the release rules for the water season base on the antecedent storage which can manage the reservoir in any situation. The impact assessment on the existing reservoir operation shows as Figure 4.3.

The existing reservoir operation in this thesis is considered 2 release rules which based on reservoir operation rule curves as shown in Table 2.13 and Figure 2.10. These release rules include general and flood release rules. The general release rule is the previous reservoir operation rule which used to regulate the reservoir in the year 1979 – 2011. While the flood release rule is the revised reservoir operation rule which suggested to regulate the reservoir by the government of Thailand in year 2012.

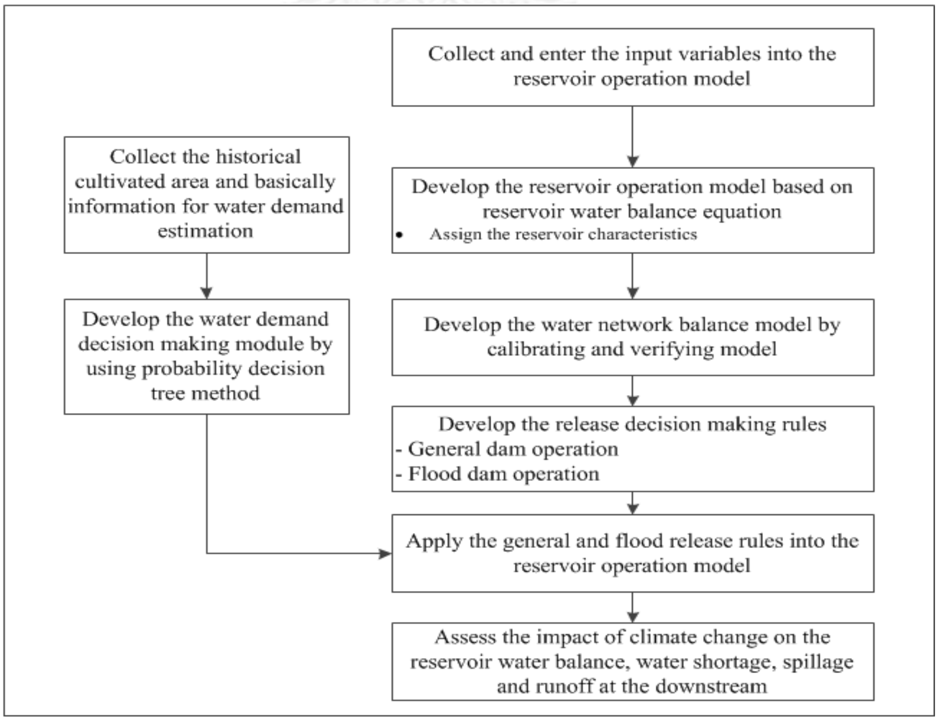


Figure 4.3 The impact assessment procedures on the existing reservoir operation

The impact assessment procedures on the existing reservoir operation modeling follow as:

1) Collect and enter the input variables into the reservoir operation model included rainfall, maximum and minimum temperature, relative humidity, initial storage, inflow and the reservoir characteristics.

2) Collect the historical cultivating area and basically information for water demand estimation in Phisanulok and Chao Phraya irrigation Projects.

3) Develop the reservoir operation model based on reservoir water balance equation.

- Enter the input variables into the reservoir operation model included rainfall, maximum and minimum temperature, relative humidity, initial storage and inflow based on monthly basis.

- Assign the reservoir characteristics such as height – volume – area curve, crest of spillway, maximum storage level, normal storage level, dead storage level and reservoir rule curve.

4) Develop the water demand decision making module by using probability decision tree method to classify from the storage at the end of season and estimate the water demand unit bases on the climate condition (see detail in Appendix D.1.6).

5) Develop the water network balance model by calibrating and verifying model with the observed runoff and integrate this model to reservoir operation model (see detail in Appendix F).

6) Develop the release rules as the water release decision module by calculating the release – storage ratio for general and flood control operation of Sirikit Dam and Bhumibol Dam (as shown in Table D.2 and D.3).

7) Apply the general and flood control release rules into the reservoir operation model. For the general and flood dam operation rules, the release (Ot) can be calculate by the following equation:

$$O_t = r_i \times S_{et-1} \tag{18}$$

where O_t is the amount of water release in the present month, Mm3/month; r_i is release-effective storage ratio, month^{-1}; S_{et-1} is the antecedent storage.

8) Assess the impact of climate change on the existing reservoir operation such as reservoir water balance, spillage, water shortage and stream flow at the downstream.

4.3 Adaptive reservoir operation development

The adaptive reservoir operation is to modify reservoir operation rules to deal with the water demand, water shortage and flood. This reservoir operation was adjusted from general reservoir operation and apply ANFIS technique to establish the ANFIS release decision making module. The adaptive reservoir operation development procedure shown in Figure 4.4. The list of data collection for adaptive reservoir operation development shows as Table 4.4 as same as the existing reservoir operation modeling.

The adaptive reservoir operation development procedures follow as:

1) Create the probability of antecedent effective storage and determine the water season, set up the water season in wet and dry season; and then classify the state variables for training the ANFIS release functions included input and output variables by using probability decision tree method.

2) Formulate the adaptive neurofuzzy inference system (ANFIS) release rules by calibrating and verifying the release rule with the actual dam operation.

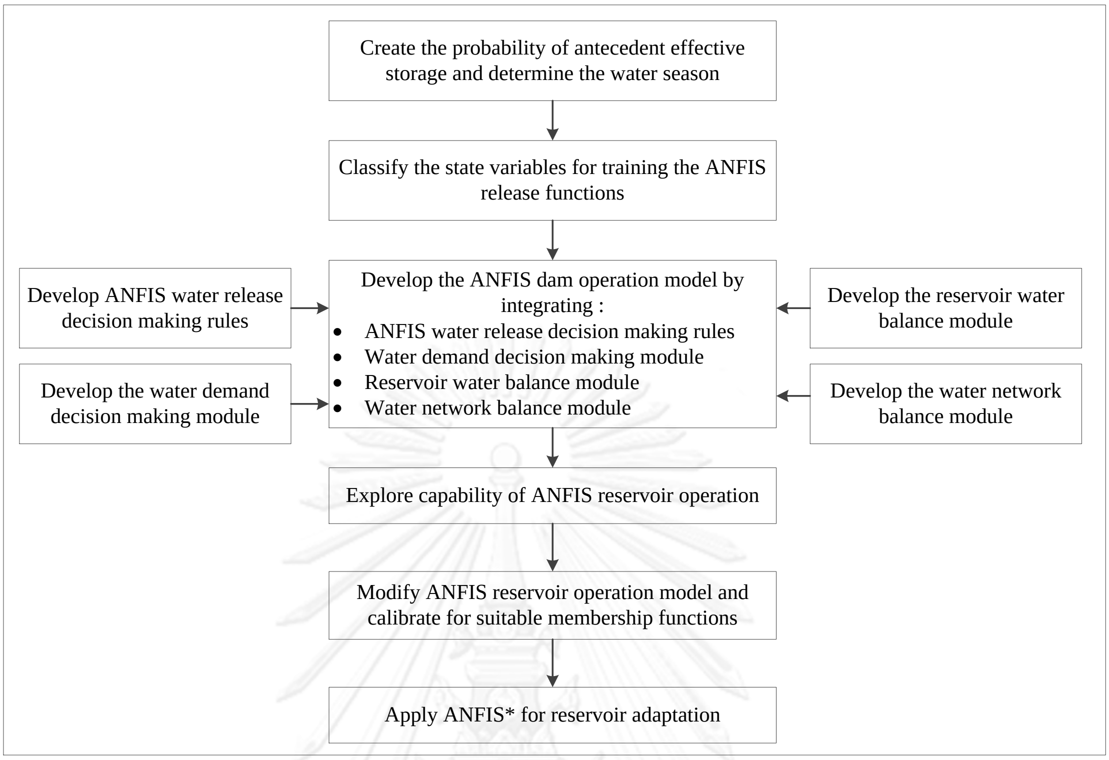


Figure 4.4 The adaptive reservoir operation development procedures

3) Develop the ANFIS dam operation model by integrating the ANFIS water release decision making rules, the water demand decision making module, the reservoir water balance module and the water network balance module.

4) Explore capability of ANFIS reservoir operation by modeling the ANFIS reservoir operation and comparing with the actual reservoir operation.

5) Modify ANFIS reservoir operation model (called ANFIS*) and calibrate for suitable membership functions by adjusting general dam operation to minimize water deficit and spillage.

6) Apply the ANFIS* dam operation model by using the bias corrected GCM hydrological input variables.

7) Compare and conclude the ANFIS* dam operation under GCM climate condition.

CHAPTER V

BIAS CORRECTION OF GCM AND CHANGE ON VARIABLES

5.1 Introduction

Climate models are the primary tools available for investigating the response of the climate system to various forcings, for making climate predictions on seasonal to decadal time scales and for making projections of future climate over the coming century and beyond (IPCC, 2013). Climate scenarios are plausible representations of the future that are consistent with assumptions about future emissions of greenhouse gases and other pollutants and with our understanding of the effect of increased atmospheric concentrations of these gases on global climate (IPCC, 2001). The applicability of these scenarios is to provide information on the expected change in global climate due to future human activities and the effect of expected changes in climate on natural systems. The suitable climate model and its scenarios is necessary for evaluating bias correction methods. There are many available GCMs in IPCC database such as CCSR model, CSIRO model, ECHAM4/OPYC3 model, GFDL model, HadCM3 model, CCCma3 model and MRI AGCM model.

The CCSR model used here is a coupled ocean-atmosphere model that consists of the CCSR/NIES atmospheric GCM, the CCSR ocean GCM, a thermodynamic sea-ice model, and a river routing model (Abe-Ouchi et al., 1996). The spatial resolution is T21 spectral truncation (roughly 5.6° latitude/longitude) and 20 vertical levels for the atmospheric part, and roughly 2.8° horizontal grid and 17 vertical levels for the oceanic part.

The CSIRO Atmospheric Research Mark 2b climate model (Hirst et al., 1996, 1999) has recently been used for a number of more sophisticated climate change simulations. The CSIRO model includes the Gent-McWilliams mixing scheme in the ocean and shows greatly reduced climate drift relative to earlier versions (e.g. Dix and Hunt, 1998).

The ECHAM4/OPYC3 model was developed at the Max Planck Institute in Hamburg, Germany, using the weather forecasting model (ECMWF) and a comprehensive parameterisation package developed at Hamburg therefore the abbreviation HAM) which allows the model to be used for climate simulations. ECHAM4 uses 2.8ox2.8o grid cells of a 19-layer atmosphere and an 11-layer ocean (Roeckner et al., 1996). The model is a spectral transform model with 19 atmospheric layers and the results used here are derived from experiments performed with spatial resolution T42 (which approximates about 2.8° longitude/latitude resolution).

The GFDL model was performed using the coupled ocean-atmosphere model (described in Manabe et al. (1991) and Stouffer et al., (1994)). The model has interactive clouds and seasonally varying solar insolation. The atmospheric component has nine finite difference (sigma) levels in the vertical. This version of the model was run at a rhomboidal resolution of 15 waves (R15) yielding an equivalent resolution of about 4.5° latitude by 7.5° longitude. The model has global geography consistent with its computational resolution and seasonal (but not diurnal) variation of insolation. The ocean model is based on that of Byan and Lewis (1979) with a spacing between grid points of 4.5° latitude and 3.7° longitude . It has 12 unevenly spaced levels in the vertical dimension.

The HadCM3 has a spatial resolution of 2.5° x 3.75° (latitude by longitude) and the representation produces a grid box resolution of 96 x 73 grid cells. This produces a surface spatial resolution of about 417 km x 278 km reducing to 295 x 278km at 45 degrees North and South (comparable to a spectral resolution of T42). The equilibrium climate sensitivity (DT2x) of HadCM3, that is the global-mean temperature response to a doubling of effective CO2 concentration, is approximately 2.5°C, although, this quantity varies with the time-scale considered.

The CCCma3 is run at two different resolutions and has a surface grid whose spatial resolution is roughly 2.8 degrees lat/lon and 31 levels in the vertical. As before the ocean grid shares the same land mask as the atmosphere, but in this case there are 6 ocean grids underlying every atmospheric grid cell. The ocean resolution is therefore approximately 1.4 degrees in longitude and 0.94 degrees in latitude. This provides slightly better resolution of zonal currents in the tropics, more nearly isotropic resolution at mid latitudes, and somewhat reduced probles with converging meridians in the Arctic (Flato and Hibler, 1992).

The MRI AGCM data was run during the period 1979–2006 on a daily basis. The concentrations of greenhouse gases (CO_2, CH_4, N_2O) and aerosols in the scenario simulation with MRI-CGCM were based on the IPCC Special Report on Emission Scenario (SRES) A1B, which assumes CO_2 increases about twice in concentration between the periods. However, the nesting of high-resolution regional model is known to have high dependency on the lateral boundary forcing and significant inability to represent regional–global-scale interaction comprehensively due to lack of two-way nesting for feedback with the forcing GCM input. Time-slice numerical simulations were made using a high performance super computer, the Earth Simulator, which was jointly developed by Japan Meteorological Agency (JMA) and Meteorological Research Institute (MRI), Japan has been used for global warming projection (Kitoh, 2008).

The emission scenarios were developed by the IPCC and published as a Special Report on Emissions Scenarios (SRES). The A1 scenario assumes rapid economic growth, a global population that will reach 9 billion in 2050 and then gradually declines, and the quick spread of new and efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. For the A1B scenario where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies. The B1 scenarios are of a world more integrated, and more ecologically friendly. The B1 scenarios are characterized by rapid economic growth as in A1, but with rapid changes towards a service and information economy, population rising to 9 billion in 2050 and then declining as in A1, reductions in material intensity and the introduction of clean and resource efficient technologies and an emphasis on global solutions to economic, social and environmental stability. For scenarios A2 and B2, two contrasting future emission scenarios were used to account for uncertainty for future GHGs/sulphate emissions data. The A2 scenario assumes an emphasis on local traditions, high population growth, and less concern for rapid economic development. The B2 scenario envisages less rapid, and more diverse technological change with emphasis on community initiative and social innovation to find local, rather than global solutions. This scenario is oriented toward environmental protection and social equity (Nakicenovic and Swart, 2000).

5.2 GCM selection

For this study, monthly precipitation scenarios from seven GCMs (21 experiments) were downloaded from the IPCC data centre. (http://www.ipcc-data.org/) prepossessed to use in the analysis, including CCSR (Center for Climate System Research National Institute for Environmental Studies Japan), CSIRO (Australia's Commonwealth Scientific and Industrial Research Organisation Australia), ECHAM4 (Max Planck Institute für Meteorologie Germany), GFDL (Geophysical Fluid Dynamics Laboratory USA), HADCM3 (Hadley Centre for Climate Prediction and Research UK) and CCCMA3 (Canadian Center for Climate Modeling and Analysis Canada). Another one is MRI GCM was distributed by Meteorological Research Institute Japan.

Summaries of the GCMs, including their type and spatial resolution are presented in Table 5.1. Sixty-five stations were used to compare the observed values and GCMs data. The GCM ability was checked for precipitation using statistical parameters: namely, root mean square error (RMSE) coefficient of determination (R^2), standard error (SE), and standard deviation (SD). Precipitation values at station location were taken from the processed GCMs scenarios based on their location (latitude and longitude).

Table 5.1 The characteristics of GCM data

GCM Name	Scenario Type	Model Resolution	Data Period
CCSR-A2	SRES – A2	2.8° x 2.8°	1979 - 2006
CSIRO-A2	SRES – A2	3.2° x 5.6°	1979 - 2006
ECHAM4-A2	SRES – A2	2.8° x 2.8°	1990 - 2006
GFDL-A2	SRES – A2	3.75° x 2.25°	1979 - 2006
HadCM3-A2	SRES – A2	2.5° x 3.75°	1979 - 2006
CCCma3-A2	SRES – A2	3.75° x 3.75°	1979 - 2006
MRI-A2	SRES – A2	0.1875° x 0.1875°	1979 - 2006
CCSR-B2	SRES – B2	2.8° x 2.8°	1979 - 2006
CSIRO-B2	SRES – B2	3.2° x 5.6°	1979 - 2006
ECHAM4-B2	SRES – B2	2.8° x 2.8°	1990 - 2006
GFDL-B2	SRES – B2	3.75° x 2.25°	1979 - 2006
HadCM3-B2	SRES – B2	2.5° x 3.75°	1979 - 2006
CCCma3-B2	SRES – B2	3.75° x 3.75°	1979 - 2006
MRI-B2	SRES – B2	0.1875° x 0.1875°	1979 - 2006
CCSR-A1B	SRES – A1B	2.8° x 2.8°	1979 - 2006
CSIRO-A1B	SRES – A1B	3.2° x 5.6°	1979 - 2006
ECHAM4-A1B	SRES – A1B	2.8° x 2.8°	1990 - 2006
GFDL-A1B	SRES – A1B	3.75° x 2.25°	1979 - 2006
HadCM3-A1B	SRES – A1B	2.5° x 3.75°	1979 - 2006
CCCma3-A1B	SRES – A1B	3.75° x 3.75°	1979 - 2006
MRI-A1B	SRES – A1B	0.1875° x 0.1875°	1979 - 2006

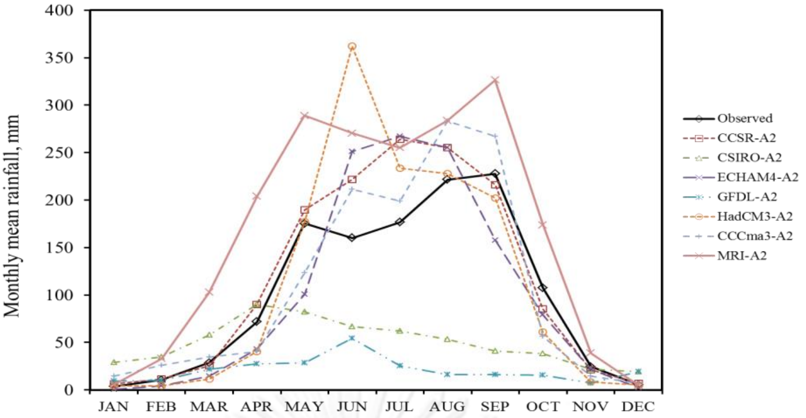
The results revealed a considerable variability regarding the GCM simulation for the observed precipitation. The MRI GCMs model is good in simulating the magnitude of spatial variability over the study area. The RMSE, CCSR, and MRI showed the lowest value, whereas the GFDL and CSIRO had the highest errors. The coefficient of determination values of the MRI model were mostly between 0.53 – 0.69, whereas the CCSR and MRI models were closest to the observed standard deviation. The statistical characteristics of precipitation data are summarized in Table 5.2. The mean of GCM precipitation was compared with the observed data shown in Figure 5.1. According to the MRI model, it has finer resolution grids that can represent local climate data. The trend in monthly mean precipitation of the CCCma3 and MRI models correspond to observed data, as shown in Figure 5.1. Observed precipitation was calculated by using Inverse Distance Weighing (IDW) method based on the data from 64 rainfall stations. The location of the stations is shown in Figure 2.2. From the statistical parameters of GCM data it was found that the MRI GCM data were more consistent with the observed data.

The GCM precipitation data were evaluated according to the accuracy of the GCM precipitation data in the present period (1979 – 2006). The goodness of fit tests were used to perform the accuracy in this study such as root mean square error (RMSE), determination of correlation (R^2), standard error (SE) and the standard deviation (SD). A comparison of goodness of fit tests of GCM precipitation data is shown in Table 5.2. Although Sharma selected the various GCMs for impact assessment on water resources in the Ping and Mae Klong River Basin, it was found that the CSIRO-MK2 and ECHAM4 model were good representatives in terms of magnitude and the spatial variability of precipitation (Sharma, 2007). However the results of this thesis revealed that CSIRO-MK2 and ECHAM4 model give a higher RMSE and lower R^2 compared with the other GCMs. Because the grid size of both models was very coarse and the characteristic of the Nan River Basin was higher spatial variability from the quite different elevation between the mountainous area at upper Nan River Basin and the flood plain area at the lower Nan River Basin. These both models can not represent the rainfall pattern in the basin scale.

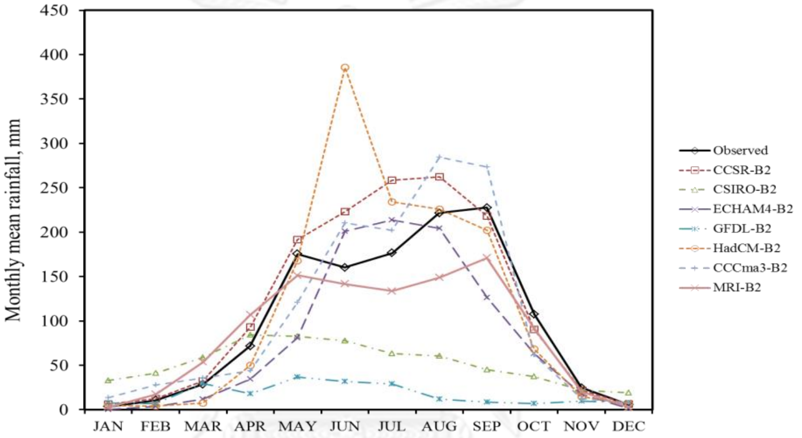
Table 5.2 Statistical summary of monthly raw GCM precipitation compared with observed

Observed/GCM	Scenario	Mean (mm/day)	SD	R^2		RMSE		SE	
				Range	Mean	Range	Mean	Range	Mean
Observed		3.37	2.91						
CCSR	A2	3.87	3.55	0.33 – 0.62	0.49	2.40 – 3.68	2.81	2.18 – 2.92	2.47
CSIRO	A2	1.66	1.5	0.00 – 0.08	0.03	3.32 – 6.01	4.23	1.10 – 2.18	1.48
ECHAM	A2	3.33	3.83	0.19 – 0.54	0.35	2.73 – 3.86	3.31	2.50 – 3.52	3.00
GFDL	A2	0.70	1.09	0.00 – 0.06	0.02	3.69 – 6.55	4.69	0.79 – 1.20	1.08
HadCM3	A2	3.72	4.46	0.25 – 0.53	0.48	3.21 – 4.79	3.77	2.71 – 4.35	3.53
CCCma3	A2	3.55	4.08	0.27 – 0.51	0.41	3.03 – 4.24	3.36	2.86 – 3.47	3.13
MRI	A2	5.52	4.08	0.45 – 0.59	0.52	1.90 – 4.89	2.49	1.43 – 4.23	2.01
CCSR	B2	3.93	3.56	0.34 – 0.63	0.49	2.15 – 3.49	2.82	2.02 – 3.16	2.59
CSIRO	B2	1.74	1.52	0.00 – 0.08	0.04	3.23 – 6.01	4.16	1.16 – 2.22	1.49
ECHAM	B2	2.66	2.83	0.21 – 0.47	0.34	2.65 – 4.02	3.34	2.34 – 3.42	2.88
GFDL	B2	0.57	1.03	0.00 – 0.03	0.01	3.77 – 6.64	4.8	1.01 – 1.04	1.02
HadCM3	B2	3.81	4.57	0.23 – 0.53	0.35	3.32 – 4.90	3.92	2.83 – 4.45	3.68
CCCma3	B2	3.59	3.54	0.21 – 0.49	0.35	2.94 – 4.16	3.55	2.36 – 3.58	2.97
MRI	B2	2.89	2.14	0.48 – 0.63	0.56	1.84 – 4.54	3.19	1.32 – 4.89	3.11
CCSR	A1B	3.90	3.50	0.29 – 0.54	0.42	2.24 – 3.72	2.98	2.05 – 3.19	2.62
CSIRO	A1B	1.70	0.76	0.07 – 0.18	0.13	2.91 – 5.34	4.13	1.78 – 2.97	2.38
ECHAM	A1B	2.99	3.18	0.24 – 0.49	0.37	2.11 – 3.56	2.84	2.30 – 3.62	2.96
GFDL	A1B	0.63	1.78	0.08 – 0.10	0.09	3.69 – 8.55	6.12	0.70 – 1.09	0.90
HadCM3	A1B	3.76	4.15	0.19 – 0.44	0.32	3.34 – 4.85	4.10	2.56 – 4.21	3.39
CCCma3	A1B	3.64	4.23	0.23 – 0.49	0.40	3.15 – 4.33	3.48	3.06 – 3.58	3.28
MRI	A1B	4.38	3.48	0.53 – 0.69	0.68	1.90 – 4.89	2.49	1.43 – 4.23	2.01

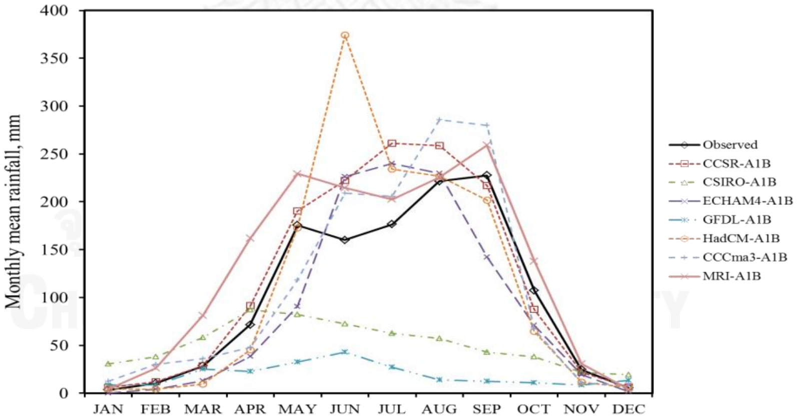
* Analyses data period is only from 1990 – 2006, unit : mm/day



(a) GCM scenario – A2



(b) GCM scenario – B2



(c) GCM scenario – A1B

Figure 5.1 Trend of monthly mean raw GCM precipitation for Nan River Basin

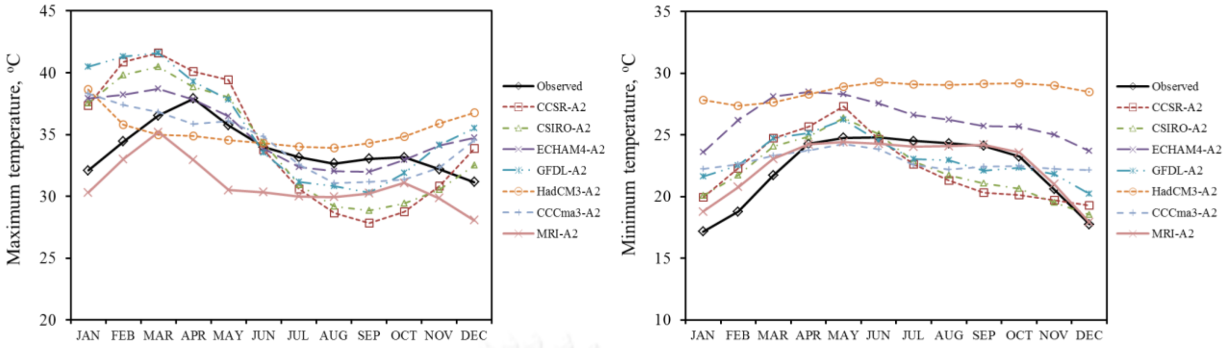
The GCM climate data which used to study the climate change in this study included maximum, minimum and mean temperature, and relative humidity. The statistical summary of monthly GCM climate data was shown in Table 5.3 to 5.6. It was found that the maximum temperature, CCSR, CSIRO, ECHAM and MRI GCM climate provided the higher correlation compared with the observed values. On the other hand, ECHAM4, CCCma and MRI provided the higher correlation in minimum temperature. From the results of correlation, the MRI–A1B was selected to study the impact of climate change. For the ECHAM4 and MRI provided the higher correlation in mean temperature. Furthermore, the mean of GCM maximum, minimum and mean temperature were compared with the observed data shown in Figure 5.2 to 5.3.

Table 5.3 Statistical summary of monthly raw GCM maximum temperature

Observed/GCM	Scenario	Mean (°C)	SD (°C)	R^2		RMSE		SE	
				Range	Mean	Range	Mean	Range	Mean
Observed		33.59	1.97						
CCSR	A2	34.18	5.38	0.45 - 0.48	0.46	3.99 - 4.29	4.14	4.02 - 4.2	4.11
CSIRO	A2	33.52	4.23	0.45 - 0.46	0.45	2.96 - 3.34	3.15	3.1 - 3.46	3.28
ECHAM	A2	34.89	2.67	0.3 - 0.32	0.31	2.45 - 2.61	2.53	2.23 - 2.41	2.32
GFDL	A2	35.64	4.54	0.24 - 0.26	0.25	3.97 - 4.62	4.295	3.86 - 4.39	4.125
HadCM3	A2	34.69	1.26	0.13 - 0.26	0.195	2.72 - 3.03	2.875	1.04 - 1.33	1.185
CCCma3	A2	33.57	2.39	0.17 - 0.29	0.23	2 - 2.48	2.24	1.94 - 2.47	2.205
MRI	A2	30.84	2.08	0.48 - 0.63	0.56	3.07 - 3.12	3.10	1.21 - 1.72	1.47
CCSR	B2	31.16	5.04	0.44 - 0.46	0.45	4.39 - 4.67	4.53	3.88 - 3.93	3.905
CSIRO	B2	33.03	3.48	0.4 - 0.45	0.43	1.92 - 3.75	2.835	1.98 - 3.51	2.745
ECHAM	B2	33.19	2.60	0.32 - 0.35	0.34	2.07 - 2.18	2.13	2.13 - 2.33	2.23
GFDL	B2	32.18	4.37	0.26 - 0.29	0.27	3.75 - 3.99	3.87	3.62 - 4.19	3.905
HadCM3	B2	34.80	1.29	0.11 - 0.22	0.17	2.75 - 3.06	2.905	1.09 - 1.39	1.24
CCCma3	B2	33.40	2.54	0.16 - 0.3	0.23	2.09 - 2.61	2.35	2.01 - 2.68	2.35
MRI	B2	30.34	2.08	0.46 - 0.63	0.55	3.13 - 4.02	3.58	1.23 - 1.72	1.48
CCSR	A1B	32.58	5.48	0.44 - 0.45	0.45	4 - 4.71	4.36	4.02 - 4.55	4.29
CSIRO	A1B	32.93	4.48	0.45 - 0.48	0.47	3.34 - 3.39	3.37	3.37 - 3.49	3.43
ECHAM	A1B	34.04	2.64	0.31 - 0.33	0.32	2.09 - 2.26	2.18	2.18 - 2.37	2.28
GFDL	A1B	33.91	4.45	0.25 - 0.27	0.26	3.42 - 3.98	3.70	3.74 - 4.29	4.02
HadCM3	A1B	34.74	1.27	0.12 - 0.24	0.18	2.73 - 3.05	2.89	1.06 - 1.36	1.21
CCCma3	A1B	33.51	2.45	0.16 - 0.32	0.24	1.98 - 2.55	2.265	1.94 - 2.57	2.255
MRI	A1B	30.43	2.04	0.48 - 0.63	0.56	3.02 - 3.93	3.475	1.21 - 1.67	1.44

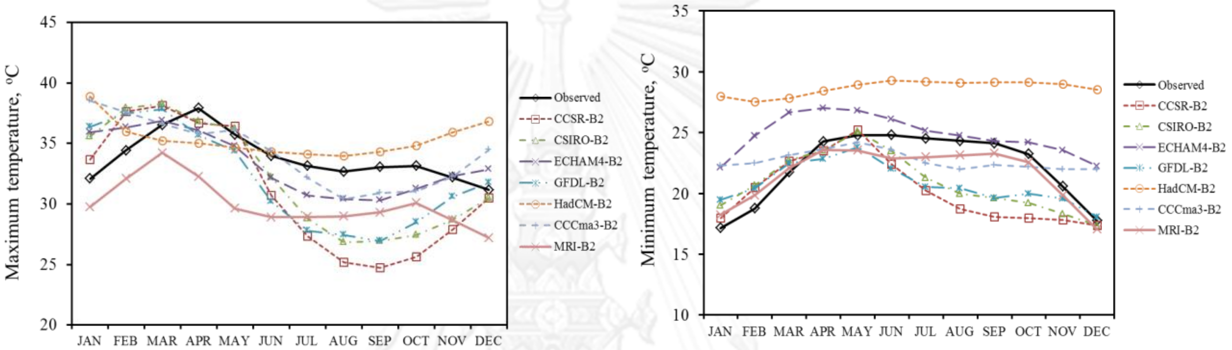
Table 5.4 Statistical summary of monthly raw GCM minimum temperature

Observed/GCM	Scenario	Mean (°C)	SD (°C)	R^2		RMSE		SE	
				Range	Mean	Range	Mean	Range	Mean
Observed		22.58	2.73						
CCSR	A2	22.75	2.88	0.18 - 0.3	0.24	2.54 - 2.94	2.74	2.34 - 2.93	2.635
CSIRO	A2	22.51	2.53	0.33 - 0.45	0.39	2.1 - 2.31	2.205	1.89 - 2.26	2.075
ECHAM	A2	26.76	1.58	0.43 - 0.53	0.48	4.54 - 4.65	4.595	1.18 - 1.19	1.19
GFDL	A2	23.71	1.91	0.12 - 0.44	0.28	2.29 - 2.91	2.6	1.35 - 2.07	1.71
HadCM3	A2	26.03	1.18	0.44 - 0.56	0.5	1.71 - 6.87	4.29	0.52 - 1.17	0.845
CCCma3	A2	22.58	1.02	0.28 - 0.75	0.515	1.65 - 2.56	2.105	0.66 - 0.68	0.67
MRI	A2	22.83	2.18	0.91 - 0.94	0.93	0.83 - 0.89	0.86	0.58 - 0.63	0.61
CCSR	B2	20.45	2.89	0.17 - 0.24	0.205	3.32 - 3.78	3.55	2.42 - 2.99	2.705
CSIRO	B2	21.18	2.52	0.31 - 0.38	0.345	2.6 - 2.8	2.7	1.98 - 2.32	2.15
ECHAM	B2	25.35	1.58	0.43 - 0.53	0.48	3.28 - 3.44	3.36	1.18 - 1.19	1.19
GFDL	B2	21.41	1.89	0.09 - 0.36	0.225	2.61 - 2.83	2.72	1.39 - 2.11	1.75
HadCM3	B2	26.11	1.13	0.47 - 0.57	0.52	1.72 - 6.93	4.325	0.47 - 1.13	0.8
CCCma3	B2	22.43	1.08	0.24 - 0.69	0.47	1.74 - 2.55	2.15	0.69 - 0.81	0.75
MRI	B2	22.33	2.10	0.91 - 0.92	0.92	0.88 - 1.08	0.98	0.62 - 0.65	0.64
CCSR	A1B	21.68	2.91	0.18 - 0.27	0.23	2.72 - 3.15	2.94	2.4 - 2.98	2.69
CSIRO	A1B	21.86	2.55	0.33 - 0.42	0.38	2.27 - 2.46	2.37	1.95 - 2.29	2.12
ECHAM	A1B	26.06	1.58	0.43 - 0.53	0.48	3.89 - 4.04	3.97	1.18 - 1.19	1.19
GFDL	A1B	22.56	1.90	0.11 - 0.4	0.26	2.16 - 2.63	2.40	1.37 - 2.09	1.73
HadCM3	A1B	26.07	1.16	0.46 - 0.57	0.52	1.71 - 6.9	4.31	0.49 - 1.15	0.82
CCCma3	A1B	22.56	1.07	0.27 - 0.72	0.50	1.66 - 2.55	2.105	0.7 - 0.75	0.725
MRI	A1B	22.43	2.14	0.93 - 0.94	0.935	0.83 - 0.95	0.89	0.55 - 0.58	0.565



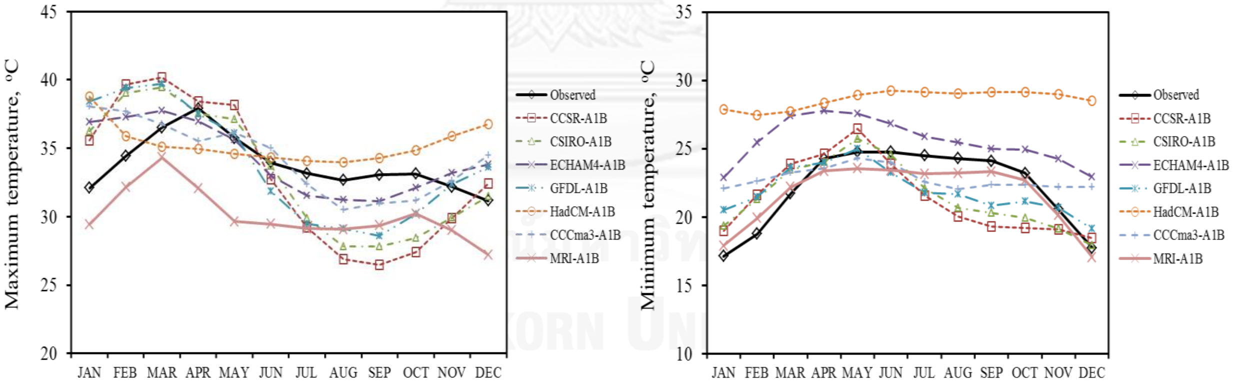
(a) Maximum temperature scenario – A2

(b) Minimum temperature scenario – A2



(c) Maximum temperature GCM scenario – B2

(d) Minimum temperature scenario – B2



(e) Maximum temperature GCM scenario – A1B

(f) Minimum temperature scenario – A1B

Figure 5.2 Trend of monthly mean GCM maximum and minimum temperature for Nan River Basin

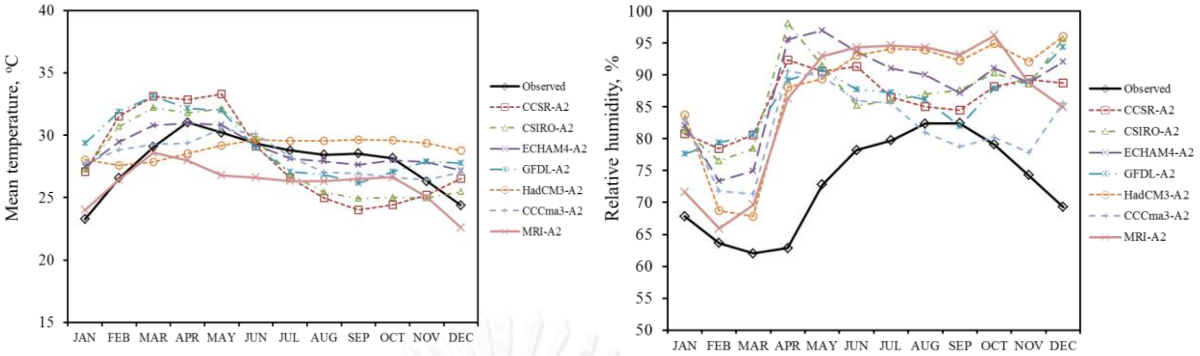
Table 5.5 Statistical summary of monthly raw GCM mean temperature

Observed/GCM	Scenario	Mean (°C)	SD (°C)	R^2		RMSE		SE	
				Range	Mean	Range	Mean	Range	Mean
Observed		27.93	2.27						
CCSR	A2	28.29	3.87	0.18 - 0.21	0.195	3.23 - 3.58	3.405	3.42 - 3.89	3.655
CSIRO	A2	27.97	3.22	0.23 - 0.28	0.255	2.68 - 2.81	2.745	2.8 - 3.03	2.915
ECHAM	A2	28.92	1.55	0.35 - 0.48	0.415	1.86 - 2.04	1.95	1.07 - 1.43	1.25
GFDL	A2	29.49	2.80	0.06 - 0.07	0.065	3.06 - 3.69	3.375	2.48 - 3.2	2.84
HadCM3	A2	28.78	0.76	0.07 - 0.12	0.095	2.17 - 2.35	2.26	0.75 - 0.77	0.76
CCCma3	A2	27.83	1.40	0.07 - 0.12	0.095	1.63 - 1.9	1.765	1.04 - 1.25	1.145
MRI	A2	26.31	1.69	0.55 - 0.73	0.64	2.06 - 2.12	2.09	0.88 - 1.24	1.06
CCSR	B2	25.44	3.88	0.16 - 0.22	0.19	3.99 - 4.43	4.21	3.46 - 3.86	3.66
CSIRO	B2	26.32	3.26	0.2 - 0.28	0.24	3.15 - 3.31	3.23	2.89 - 3.06	2.975
ECHAM	B2	27.51	1.55	0.35 - 0.48	0.42	1.68 - 1.79	1.74	1.07 - 1.43	1.25
GFDL	B2	26.62	2.78	0.06 - 0.08	0.07	3.15 - 3.38	3.265	2.45 - 3.17	2.81
HadCM3	B2	28.87	0.70	0.08 - 0.13	0.11	2.19 - 2.37	2.28	0.69 - 0.71	0.7
CCCma3	B2	27.68	1.47	0.08 - 0.13	0.11	1.72 - 2.02	1.87	1.14 - 1.37	1.26
MRI	B2	25.80	1.65	0.51 - 0.69	0.60	2.2 - 2.93	2.57	0.94 - 1.24	1.09
CCSR	A1B	26.96	3.90	0.17 - 0.22	0.20	3.34 - 3.74	3.54	3.46 - 3.88	3.67
CSIRO	A1B	27.16	3.26	0.22 - 0.29	0.26	2.81 - 2.94	2.88	2.86 - 3.04	2.95
ECHAM	A1B	28.22	1.55	0.35 - 0.48	0.42	1.62 - 1.8	1.71	1.07 - 1.43	1.25
GFDL	A1B	28.05	2.79	0.06 - 0.08	0.07	2.74 - 3.25	3.00	2.46 - 3.18	2.82
HadCM3	A1B	28.83	0.73	0.07 - 0.12	0.10	2.18 - 2.36	2.27	0.72 - 0.74	0.73
CCCma3	A1B	27.78	1.47	0.07 - 0.12	0.10	1.63 - 1.97	1.8	1.09 - 1.35	1.22
MRI	A1B	25.90	1.65	0.55 - 0.73	0.64	2.08 - 2.81	2.445	0.88 - 1.17	1.025

It was found that the relative humidity, ECHAM4, HadCM3 and MRI GCM climate provided the higher correlation compared with the observed values. On the other hand, ECHAM4, HadCM3 and MRI provided the higher correlation in relative humidity. From the results of correlation, the MRI–A1B was selected to study the impact of climate change. Furthermore, the mean of GCM relative humidity was compared with the observed data shown in Figure 5.3.

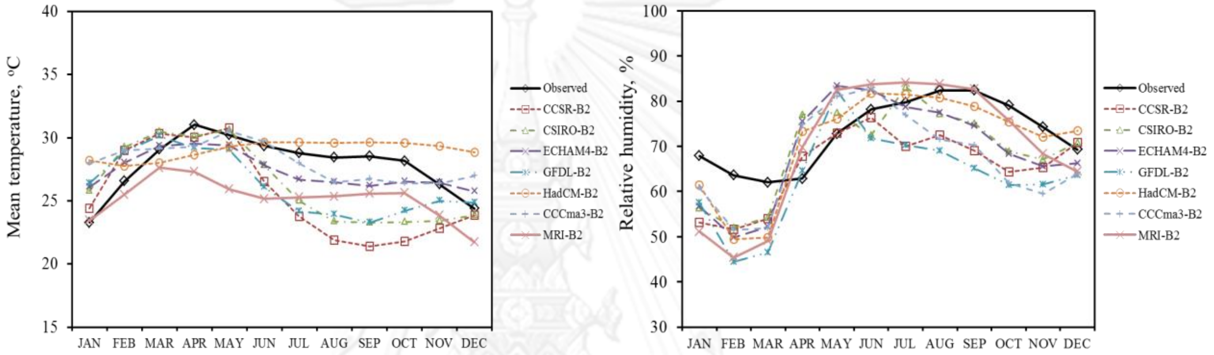
Table 5.6 Statistical summary of monthly raw GCM relative humidity

Observed/ GCM	Scenario	Mean (%)	SD (%)	R^2		RMSE		SE	
				Range	Mean	Range	Mean	Range	Mean
Observed		71.82	7.33						
CCSR	A2	84.95	5.62	0.05 - 0.1	0.075	14.89 - 15.38	15.135	4.57 - 6.65	5.61
CSIRO	A2	85.98	7.44	0.12 - 0.16	0.14	16.27 - 16.75	16.51	6.62 - 8.17	7.39
ECHAM	A2	86.52	8.10	0.22 - 0.34	0.28	15.84 - 16.94	16.39	7 - 7.38	7.19
GFDL	A2	85.51	5.96	0.05 - 0.07	0.06	15.26 - 16.42	15.84	5.16 - 6.96	6.06
HadCM3	A2	86.40	10.85	0.36 - 0.55	0.455	16.23 - 16.91	16.57	6.89 - 10.06	8.475
CCCma3	A2	79.93	7.18	0.04 - 0.04	0.04	11.79 - 12.35	12.07	6.43 - 8.35	7.39
MRI	A2	85.66	11.38	0.52 - 0.68	0.60	14.5 - 16.57	15.54	6.45 - 8.63	7.54
CCSR	B2	63.31	9.49	0.22 - 0.42	0.32	9.68 - 13.42	11.55	6.65 - 9.83	8.24
CSIRO	B2	66.85	10.94	0.33 - 0.41	0.37	8.34 - 11.23	9.785	8.18 - 10.12	9.15
ECHAM	B2	69.40	13.49	0.43 - 0.6	0.52	9.06 - 10.62	9.84	9.11 - 10.34	9.73
GFDL	B2	65.57	12.19	0.34 - 0.35	0.35	11.23 - 12.64	11.93	8.8 - 11.85	10.32
HadCM3	B2	71.55	14.07	0.48 - 0.64	0.56	6.96 - 12.37	9.665	7.2 - 12.64	9.92
CCCma3	B2	73.80	13.51	0.26 - 0.53	0.40	10.59 - 15.16	12.88	9.56 - 11.79	10.68
MRI	B2	69.49	14.90	0.65 - 0.7	0.68	9.33 - 10.07	9.70	8.47 - 9.36	8.92
CCSR	A1B	77.48	10.77	0.14 - 0.34	0.24	9.3 - 12.8	11.05	7.43 - 12.47	9.95
CSIRO	A1B	78.70	11.32	0.26 - 0.36	0.31	11.04 - 11.95	11.50	8.55 - 11.23	9.89
ECHAM	A1B	81.29	13.35	0.4 - 0.5	0.45	11.43 - 15.72	13.58	9.41 - 11.19	10.30
GFDL	A1B	79.56	10.69	0.21 - 0.29	0.25	8.25 - 16.15	12.20	6.93 - 12.6	9.77
HadCM3	A1B	79.52	13.29	0.61 - 0.63	0.62	9.9 - 13.11	11.51	7.37 - 9.79	8.58
CCCma3	A1B	78.52	13.54	0.24 - 0.53	0.39	9.96 - 15.16	12.56	9.75 - 11.79	10.77
MRI	A1B	77.99	14.90	0.65 - 0.7	0.67	10.56 - 11.94	11.25	8.47 - 9.36	8.915



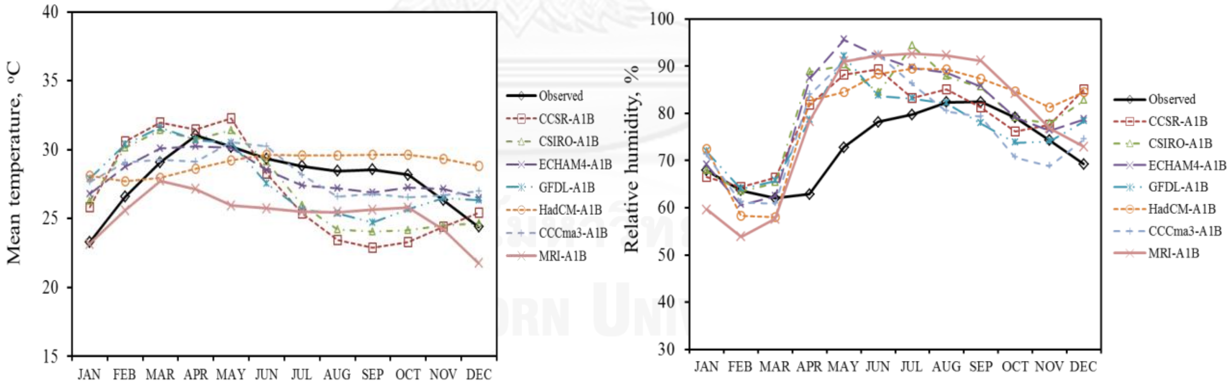
(a) Mean temperature scenario – A2

(b) Relative humidity scenario – A2



(c) Mean temperature GCM scenario – B2

(d) Relative humidity scenario – B2



(e) Mean temperature GCM scenario – A1B

(f) Relative humidity scenario – A1B

Figure 5.3 Trend of monthly mean GCM mean temperature and relative humidity for Nan River Basin

For the results, it implied the GCM model which provided the higher mean precipitation can be used to study the flood situation. Other another hand, the lower mean precipitation can be used to study the drought or the water management. Furthermore, the GCM models which give higher temperature and relative humidity can be used to apply for study for the water demand. The results revealed that the MRI-A1B had good performance and could be used to evaluate the change on the hydrological model. Because the MRI-A1B GCM simulated the global climate based on the moderate emission scenario of the IPCC special report, which provided the mean rainfall, temperature and relative humidity in the moderate increasing rate. It can be utilized for representing the future climate to study for both flood and drought situation.

5.3 The comparative study of bias correction methods

Statistical bias corrections methods were adopted to compare the performance of the bias correction method, including the Gamma-Gamma transformation method, the hybrid method, the standard deviation (SD) method, and the modified rescaling method based on the literature review. The results were compared in terms of the statistical inferences such as mean, maximum, minimum and standard deviation. On the other hand, the goodness of fit test for temporal and spatial distribution also was also used to compare each method, such as the sum of absolute errors (SAE) and the sum of squared residuals (SSR). Furthermore, the probability was used to study the uncertainty of the bias correction methods The results are as follows:

5.3.1 Temporal bias correction

The correspondence between the observed data and the acceptance of a specific bias correction method was based on the statistical inferences drawn from the comparison. The statistical inferences drawn from the comparison of the observed and bias corrected GCM monthly rainfall data are provided in Table 5.7. The hybrid method yielded the highest correlation coefficient of 0.87 compared to other bias correction methods, while the raw GCM data provided a correlation coefficient of 0.68. Furthermore, the hybrid bias correction method provided the lowest RMSE value (52.83) and SE (46.54) value compared to other bias correction methods.

Table 5.7 Statistical inferences from comparison of observed and bias corrected GCM monthly rainfall

Method	SD	R^2	RMSE	SE
Observed	94.55			
Raw-GCM	104.41	0.68	74.75	60.22
GG-GCM	88.42	0.73	61.63	55.40
SD Ratio-GCM	95.11	0.81	57.85	55.30
Hybrid-GCM	84.71	0.87	52.83	46.54
Rescale-GCM	88.67	0.68	62.42	51.08

A comparison of the statistical parameters was used to evaluate the performance of bias correction methods, as seen in Table 5.8. Furthermore, according to the comparison of the sum of absolute errors and sum of square residuals of the bias corrected GCM monthly rainfall in August – September – October and February – March – April in terms of time series shown in Table 5.9, the hybrid method yielded lower SAE and SSR values in August – September – October. However, the SD Ratio method yielded lower SAE and SSR values for the February – March – April.

The cumulative probability distribution curves for the average monthly rainfall amount during the period of three months from August to October deduced from the observed rainfall amount, the raw MRI-GCM and the bias-corrected GCM are shown in Figure 5.5. The SD ratio and hybrid method reproduced the observed distribution pattern quite successfully except for the range 33.36-98.87 mm/month and 42.67-159.07 mm/month when the two methods underestimate and for over 250.20 and 218.88 mm/month, during which the two methods overestimate the distribution pattern. Based on these inferences, the hybrid-GCM method was considered the most appropriated approach for temporal bias correction of rainfall data.

Table 5.8 Comparison of relative observed rainfall and bias corrected GCMs in monthly basis

(a) Maximum and minimum

Month	Maximum					Minimum				
	Raw	GG	SD-Ratio	Hybrid	Rescale	Raw	GG	SD-Ratio	Hybrid	Rescale
January	1.26	2.83	1.19	1.28	1.08	2.72	0.96	1.21	1.44	4.98
February	1.63	1.44	0.66	1.13	1.38	0.05	0.01	0.33	0.01	0.10
March	1.53	1.34	1.12	0.86	1.29	2.13	3.09	1.05	2.93	3.41
April	1.33	1.22	0.82	0.75	1.13	5.58	4.33	1.45	2.85	4.71
May	1.09	0.92	1.04	0.79	0.93	2.82	2.07	1.52	1.89	2.40
June	1.10	0.92	0.95	0.84	0.93	1.76	1.15	1.06	1.02	1.46
July	0.91	0.76	0.88	0.74	0.77	2.07	1.58	1.45	1.47	1.74
August	0.74	0.64	0.73	0.64	0.64	1.20	1.02	0.95	0.96	1.02
September	0.99	0.95	0.91	0.89	0.83	1.54	0.93	1.14	1.25	1.31
October	1.09	0.82	1.19	0.84	0.91	3.42	1.60	1.66	2.12	2.81
November	1.08	0.83	0.88	0.69	0.91	3.39	0.65	1.35	1.55	3.23
December	0.42	0.28	0.56	0.34	0.36	0.10	0.03	0.03	0.03	0.17

(b) Mean and standard deviation

Month	Mean					Standard deviation				
	Raw	GG	SD-Ratio	Hybrid	Rescale	Raw	GG	SD-Ratio	Hybrid	Rescale
January	1.22	1.01	0.99	1.08	1.07	1.18	1.90	1.02	1.09	1.01
February	2.27	1.83	0.92	1.27	1.94	1.71	1.49	0.67	1.09	1.45
March	2.61	2.34	1.01	1.32	2.21	1.17	1.11	0.94	0.73	0.99
April	2.14	1.79	1.00	1.15	1.80	0.82	0.85	0.76	0.47	0.70
May	1.29	1.02	1.00	0.90	1.09	0.52	0.50	0.83	0.46	0.45
June	1.34	1.04	1.00	0.93	1.13	0.76	0.80	0.84	0.72	0.65
July	1.19	0.91	1.00	0.92	1.01	0.57	0.57	0.80	0.56	0.48
August	1.09	0.90	1.00	0.91	0.93	0.39	0.42	0.58	0.40	0.34
September	1.17	0.97	1.00	0.99	0.99	0.60	0.75	0.73	0.60	0.50
October	1.28	0.84	1.01	0.86	1.07	0.80	0.78	1.00	0.61	0.66
November	1.26	0.68	0.95	0.78	1.05	0.97	0.68	0.79	0.63	0.81
December	0.85	0.32	0.91	0.63	0.75	0.54	0.28	0.67	0.43	0.47

Remark : Bias corrected rainfall divided by observed rainfall

Table 5.9 The sum of absolute errors and sum of square residuals of bias corrected GCM monthly rainfall in August – September – October and February – March – April in term of seasonal

Method	ASO		FMA	
	SAE	SSR	SAE	SSR
Raw-GCM	6,171 (5)	746,283 (5)	4,575 (5)	468,506 (5)
GG-GCM	5,334 (3)	576,569 (4)	3,712 (4)	312,414 (4)
SD Ratio-GCM	5,273 (2)	556,994 (2)	2,064 (1)	112,500 (1)
Hybrid-GCM	4,742 (1)	458,016 (1)	2,212 (2)	121,108 (2)
Rescale-GCM	5,371 (4)	575,391 (3)	3,652 (3)	297,884 (3)

Remark SAE : Sum of absolute errors , SSR : Sum of square residuals

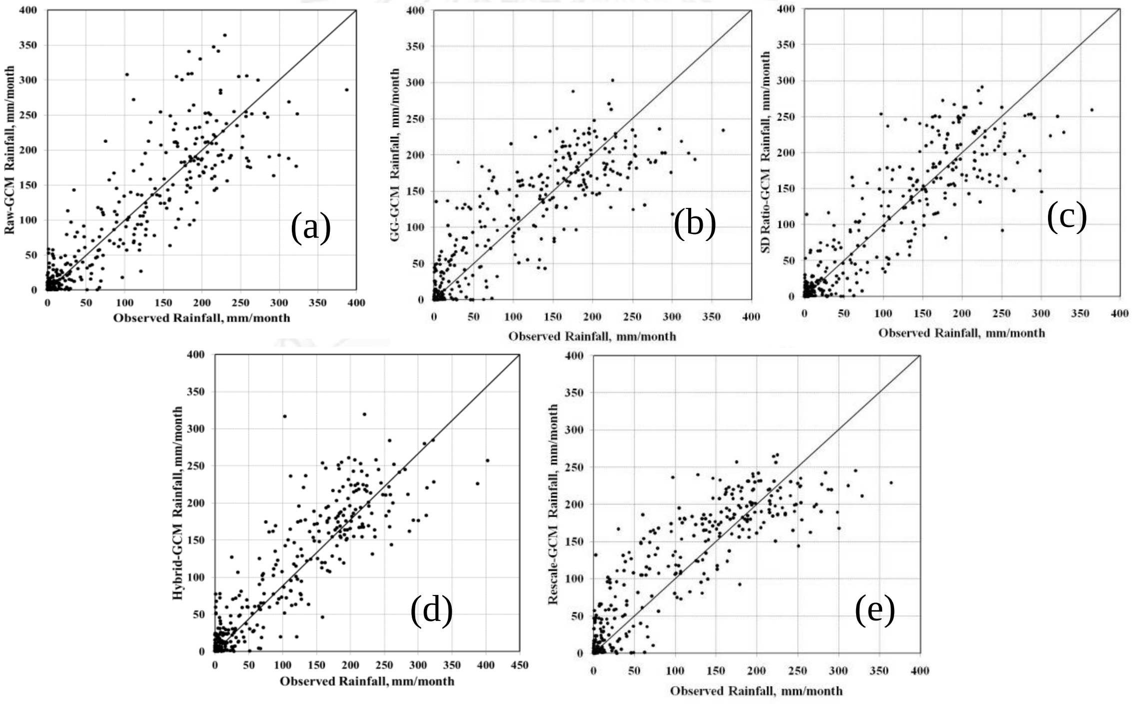
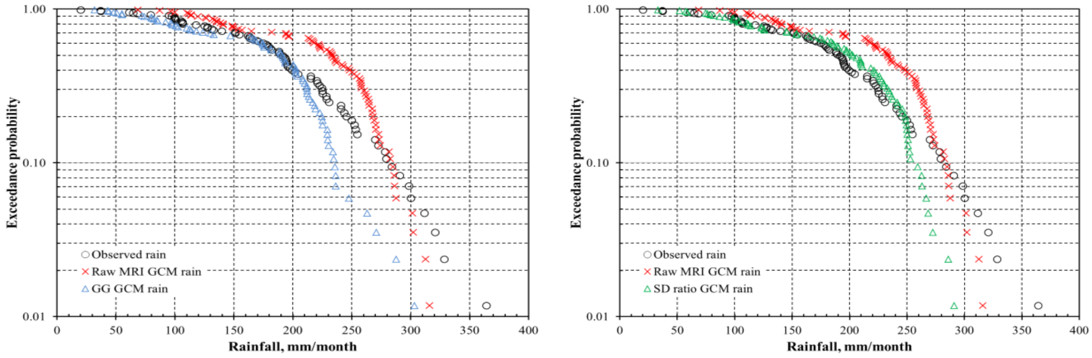
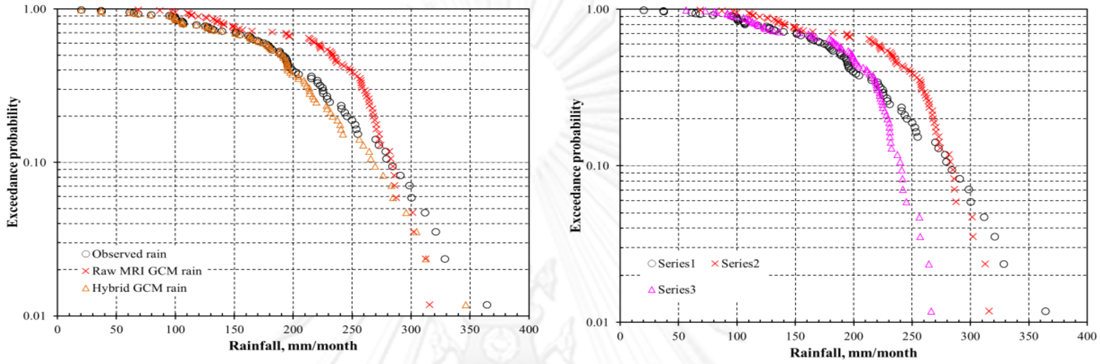


Figure 5.4 Relationships between observed and bias corrected rainfall in Nan River Basin over the period 1979 – 2006 (a) Raw – GCM, (b) GG – GCM, (c) SD Ratio – GCM, (d) Hybrid – GCM, and (e) Rescale – GCM

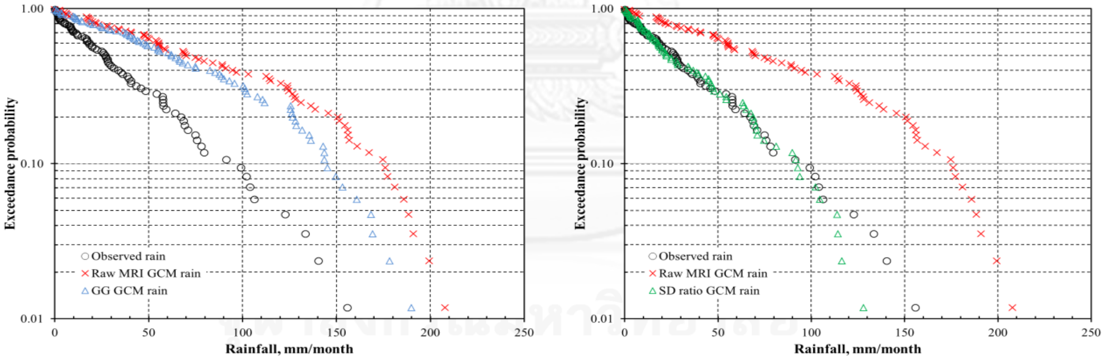


(1) GG – GCM (2) SD Ratio– GCM

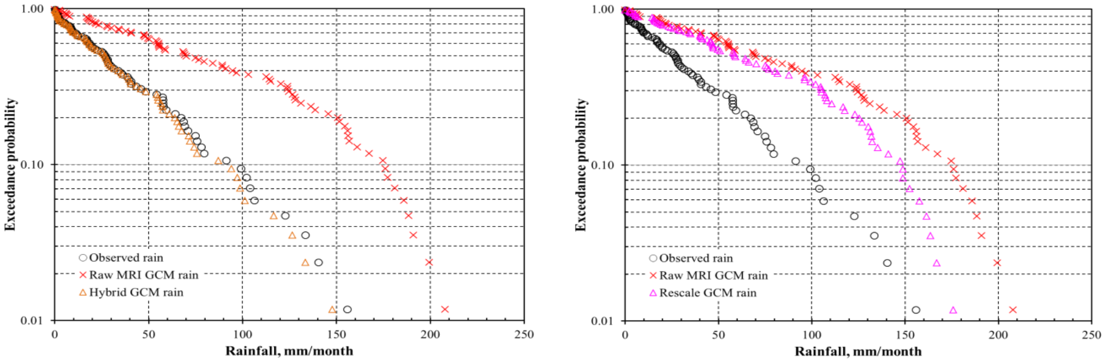


(3) Hybrid – GCM (4) Rescale – GCM

Figure 5.5 Probability curve of rainfall amount in August-September-October



(1) GG – GCM (2) SD Ratio– GCM



(3) Hybrid – GCM (4) Rescale – GCM

Figure 5.6 Probability curve of rainfall amount in February-March-April

5.3.2 Spatial bias correction

The spatial distribution patterns in wet season (August - September - October (ASO)) and dry season (February – March – April (FMA)) were generated by the inverse distance square method. They were compared to the bias-corrected GCM with the observed rainfall map shown in Figure 5.7 and 5.8. The raw GCM rain map produces more rainfall in a spatial sense compared to the observed rainfall map. The hybrid bias corrected map was found to be closer to the average observed rain field with less residual range variation, as shown in Figures 5.7(d), 5.7(e), 5.8(d) and 5.8(e). The hybrid method yields the lower values of SAE and SSR compared with the other methods, as can be seen in Table 5.10. However, the values of less rainfall of the hybrid bias corrected map were found to be more in the region of a high rainfall amount (Lower Nan River Basin). While the GG and Rescale bias corrected map are found to be higher to the average observed rain field with more residual range variation.

As a summary, the hybrid bias correction provided the better results compared with other GCMs, so it would be adopted to correct the bias from the future GCM climate data.

Table 5.10 The sum of absolute errors and sum of square residuals for spatial distribution pattern in August – September – October (ASO) and February – March – April (FMA)

Method	ASO		FMA	
	SAE	SSR	SAE	SSR
Raw-GCM	10,226	2,308,496	11,153	2,063,195
GG-GCM	5,617	515,337	8,419	1,075,381
SD Ratio-GCM	52	109	82	173
Hybrid-GCM	34	35	49	44
Rescale-GCM	7,068	1,226,717	8,170	1,152,861

Remark SAE : Sum of absolute errors , SSR : Sum of square residuals

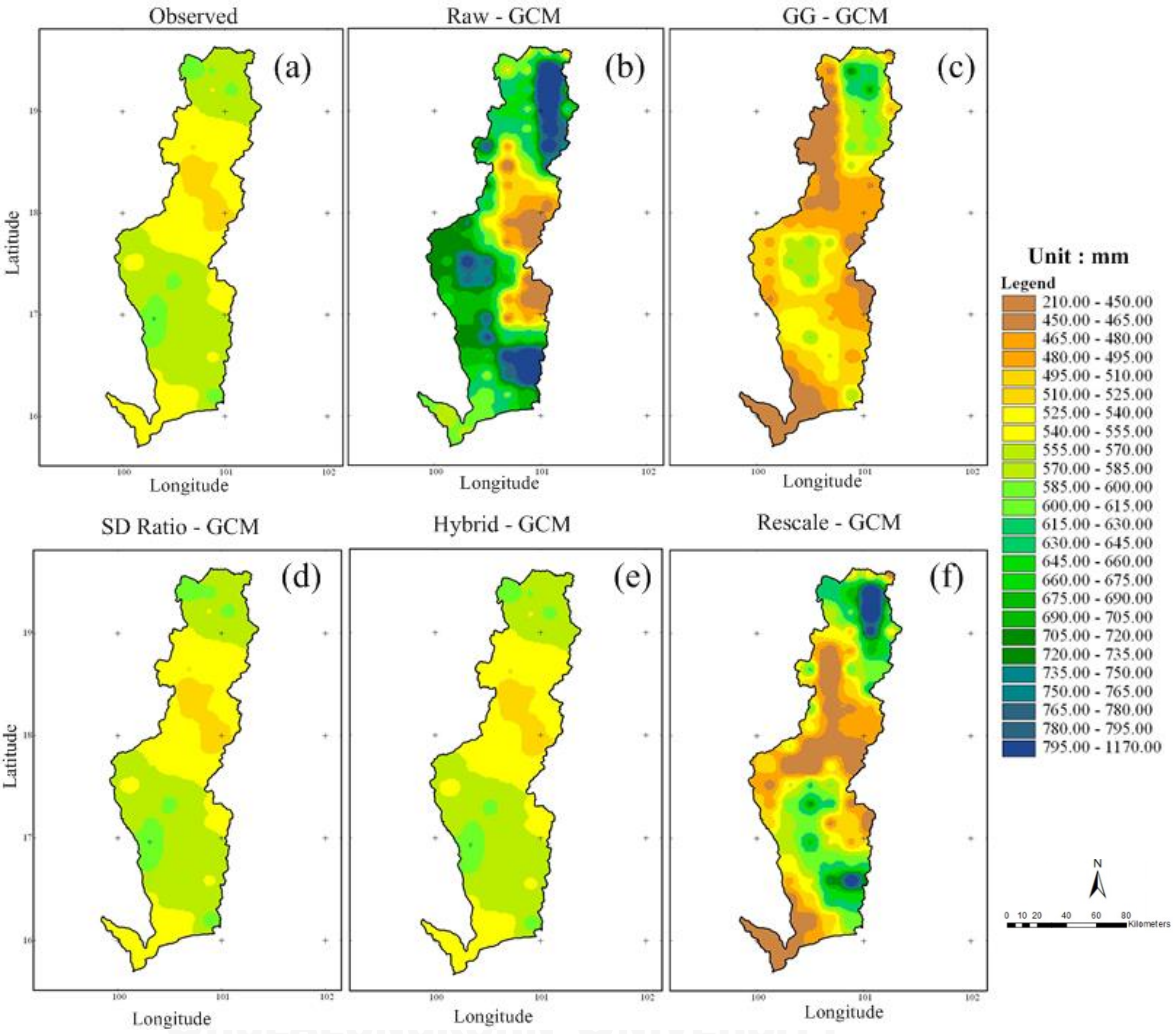


Figure 5.7 Spatial distribution pattern in August – September – October shows (a) average observed rainfall, (b) average raw – GCM, (c) average GG – GCM, (d) SD Ratio – GCM, (e) Hybrid – GCM, (f) Rescale – GCM

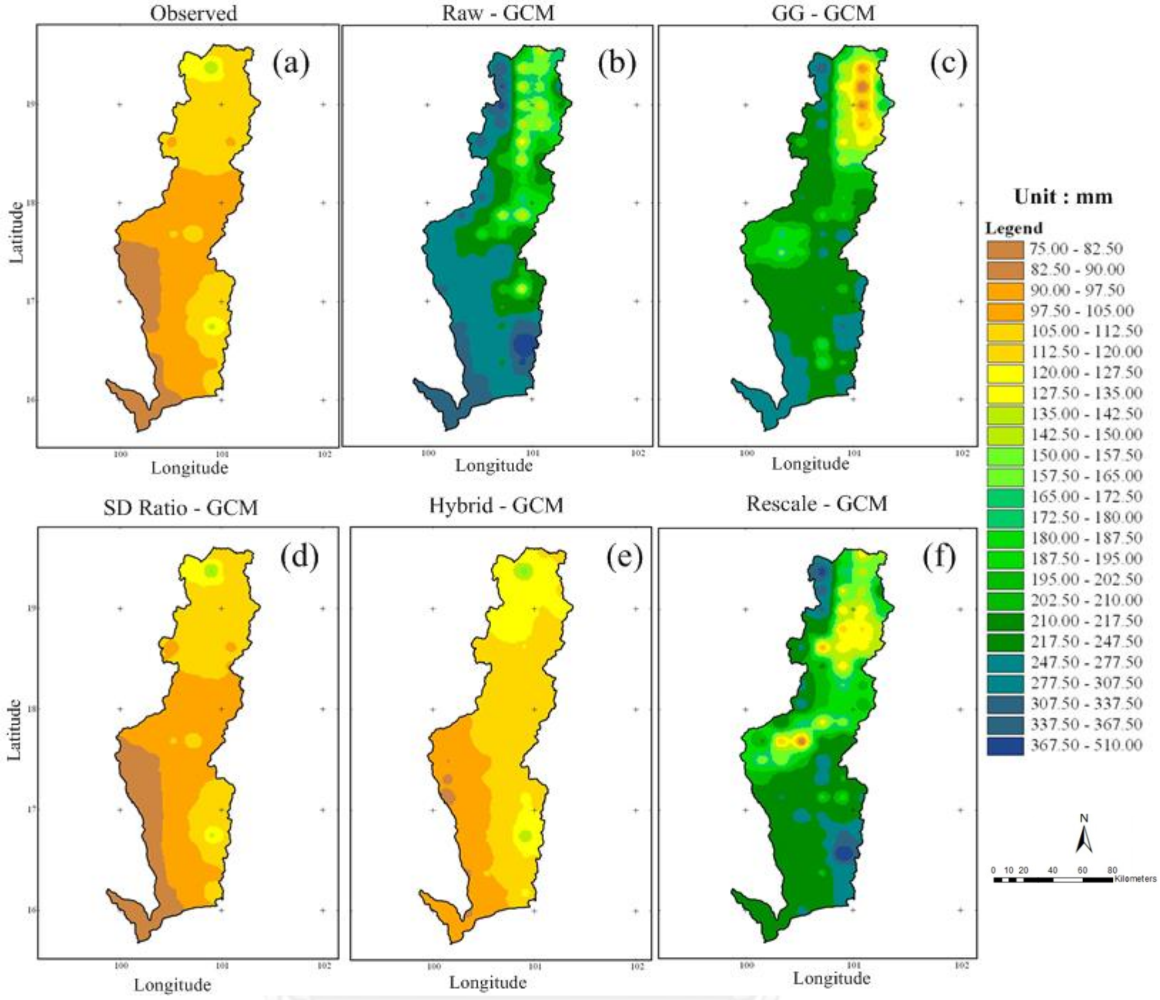


Figure 5.8 Spatial distribution pattern in February-March-April shows (a) average observed rainfall, (b) average raw – GCM, (c) average GG – GCM, (d) SD Ratio – GCM, (e) Hybrid – GCM, (f) Rescale – GCM

Precipitation bias is the main factor related to the application of GCM scenarios to assess the impact of climate change on water resources at the basin level. The comparison of different bias correction methods is presented, and the evaluation of the bias correction methods are applied to the MRI SRES A1B precipitation scenario for use in high-resolution impact assessment models. The hybrid bias correction method was found to be the best in downscaling, as it gives better correlation with respect to monthly rainfall amounts in time series terms and the lowest root mean square error with respect to monthly rainfall intensity. The SD

Ratio and Hybrid-GCM method provide a probability distribution pattern for rainfall closer to the observed pattern, except for lower and higher rainfall intensity. The hybrid method reduces the biases as well in the high intensity rainfall in rainy season, while the SD Ratio method is able to reduce biases as well in the low intensity rainfall in the dry season. The monthly mean rainfall distribution pattern in the rainy season, the SD Ratio-GCM, and the Hybrid-GCM values were found to be close to the average observed rain field with less residual range variation.

From the results, it can be implied that the hybrid method is suitable for the application to study in floods or extreme rainfall situations, water balance, and drought situations.

5.4 Trend of climate and rainfall change

5.4.1 Trend of climate change

Regarding the GCM selection procedures, the results showed that the MRI GCM gives the best performance compared with the other GCMs, so this study applied the GCM to the evaluation of climate change. The climate variables in this study include monthly maximum, minimum and mean temperature with evapotranspiration in present (1979-2006), near future (2015-2039) and far future (2075-2099). The study area for climate change assessment includes the Upper Nan River Basin and Lower Nan River Basin in Thailand (see the location details in Appendix A). The inverse distance weighted average method (IDW) was used to average the temperature from the observed stations and the GCM grid points in both the Upper Nan River Basin and Lower Nan River Basin.

The hybrid bias correction method was adopted to correct the bias of the MRI GCM as with GCM precipitation. The maximum, minimum, and mean temperature data were used to calculate the evapotranspiration using the Penman–Monteith method (Smith, 1990: 47-58). These climate data were used as the hydrological input variables for estimating the irrigation water demand, as the change of these climates will affect the irrigation water demand. The change of climate was evaluated according to mean and standard deviation by comparing the future period with the present period. The area of concern (Lower Chao Phraya River Basin) which was used to calculate the water demand and the change evaluation is shown in Figure B.1.

5.4.1.1 Upper Nan River Basin

The maximum, minimum, and mean temperature with evapotranspiration in the Upper Nan River Basin Dam in the present (1979-2006), near future (2015-2039) and far future (2075-2099) are shown in Table 5.11, and Figure 5.9. Table 5.11 shows a summary of mean and standard deviation on a seasonal and annual basis.

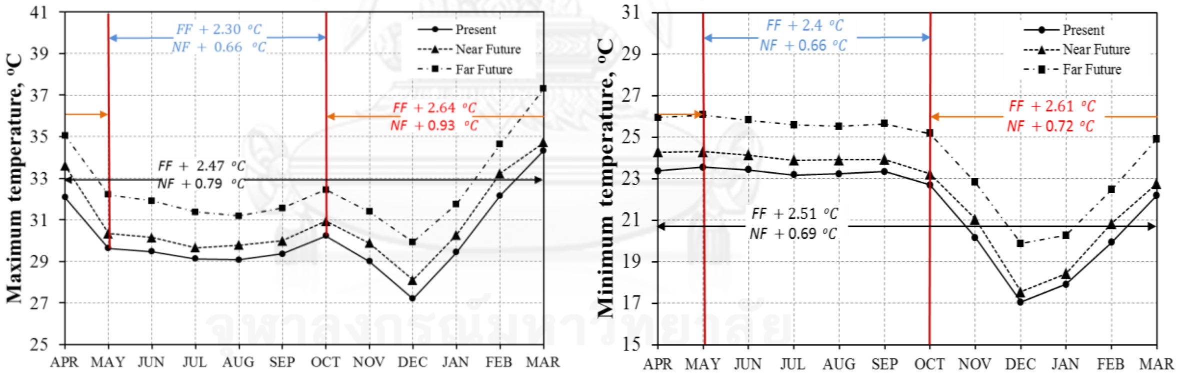
Regarding the near future, it was found that maximum, minimum and mean temperature will tend to increase in the wet season (May–October) by 0.66 °C, 0.66 °C and 0.72 °C, and it will be especially high in May; it will increase high in the dry season (November–April) by 0.93 °C, 0.72 °C and 0.91 °C, and will be especially high in April. The mean of the annual maximum, minimum and mean temperature will increase by 0.79 °C, 0.69 °C and 0.81 °C, and the standard deviation will increase 0.16, 0.12 and 0.19. While the seasonal evapotranspiration will not change significantly (change less 5%) in either the wet or dry season (+2.11% and +2.25%). The annual evapotranspiration will not change significantly (+2.18%) but the standard deviation will increase 36.67%.

In the far future, it was found that the mean maximum, minimum and mean temperature will tend to increase in the wet season (May – October) by 2.30 °C, 2.40 °C and 2.73 °C, and will be especially high in May; it will increase high in the dry season (November – April) by 2.64 °C, 2.61 °C and 2.71°C, and will be especially high in May. The mean of the annual maximum, minimum, and mean temperature will increase by 2.47 °C, 2.51 °C and 2.54 °C and the standard deviation will decrease by -0.02, -0.01 and -0.03. While the seasonal evapotranspiration will increase in both the wet and dry seasons (7.52% and 8.58%). The annual evapotranspiration will increase 8.07% and standard deviation will increase 35.83%.

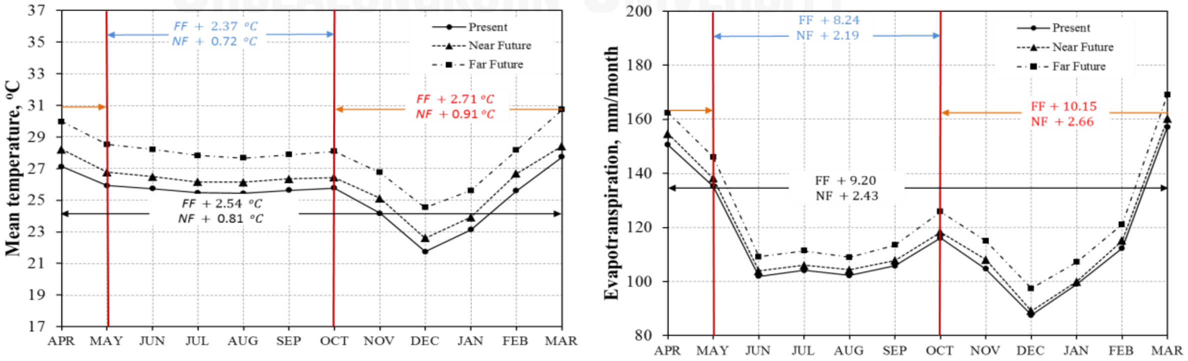
Table 5.11 Summary of mean and standard deviation climate in Upper Nan River Basin

Climate	Season/ annual	Mean					Standard deviation				
		P	NF	Relative change	F	Relative change	P	NF	Relative change	F	Relative change
Maximum temperature, °C	Wet	29.48	30.14	0.66	31.78	2.30	0.28	0.27	-0.01	0.27	0.00
	Dry	30.70	31.64	0.93	33.34	2.64	0.53	0.81	0.28	0.49	-0.04
	Annual	30.09	30.89	0.79	32.56	2.47	0.34	0.50	0.16	0.31	-0.02
Minimum temperature, °C	Wet	23.24	23.90	0.66	25.64	2.40	0.20	0.22	0.02	0.25	0.05
	Dry	20.10	20.82	0.72	22.71	2.61	0.42	0.62	0.20	0.38	-0.03
	Annual	21.67	22.36	0.69	24.17	2.51	0.27	0.40	0.12	0.27	-0.01
Mean temperature, °C	Wet	25.67	26.39	0.72	28.04	2.37	0.23	0.27	0.04	0.24	0.02
	Dry	24.92	25.83	0.91	27.62	2.71	0.43	0.74	0.31	0.39	-0.04
	Annual	25.29	26.11	0.81	27.83	2.54	0.28	0.47	0.19	0.25	-0.03
Evapotrans-piration, mm/month	Wet	665	679	2.11%	715	7.52%	4.4	4.8	9.09%	5.6	27.27%
	Dry	711	727	2.25%	772	8.58%	11.6	13.2	13.79%	12.5	7.76%
	Annual	1376	1406	2.18%	1487	8.07%	12.0	16.4	36.67%	16.3	35.83%

<u>Remark</u> : P = Present (1979 – 2006) , NF = Near future (2015 – 2039) and FF = Far future (2075 – 2099),
For temperature was calculated in difference: relative change for near future = NF – P; relative change for far future = FF – P,
For evapotranspiration was calculated in percentage: %relative change for near future = (NF-P)/P*100; %relative change for far future = (FF-P)/P*100



(a) Maximum temperature (b) Minimum temperature



(c) Mean temperature (d) Evapotranspiration

Figure 5.9 The monthly mean climate in Upper Nan River Basin

5.4.1.2 Lower Nan River Basin

The maximum, minimum, and mean temperature with evapotranspiration in the Lower Nan River Basin Dam in the present (1979-2006), near future (2015-2039) and far future (2075-2099) are shown in Table 5.12 and Figure 5.10. Table 5.12 shows a summary of the mean and standard deviation on a seasonal and annual basis.

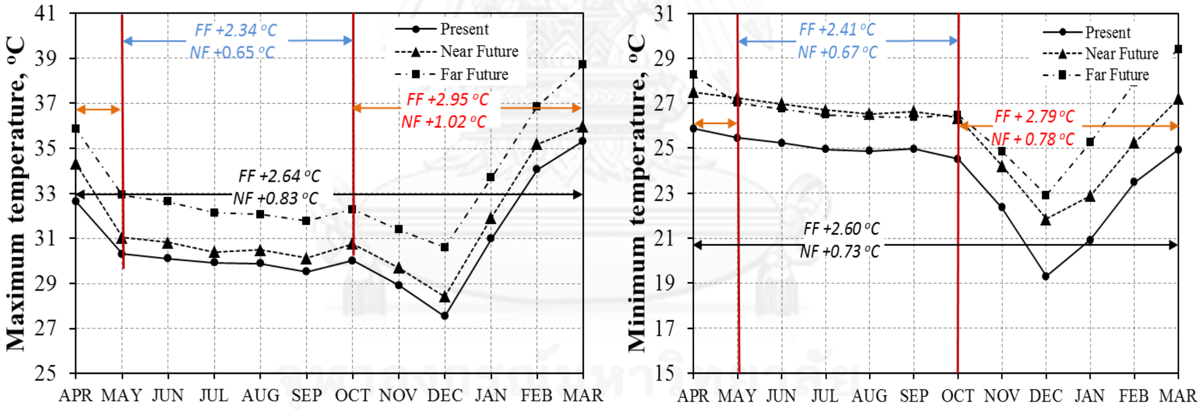
In the near future, it was found that the mean maximum, minimum and mean temperature will tend to increase in the wet season (May – October) by 0.65 °C, 0.67 °C and 0.72 °C, and be especially high in May; and it will increase high in the dry season (November – April) by 1.02 °C, 0.78 °C and 0.97 °C and be especially high in March. The mean of annual temperature will increase by 0.83 °C, 0.73 °C and 0.84 °C, and the standard deviation will increase 0.15, 0.14 and 0.19. While the seasonal evapotranspiration will not change significantly (change less 5%) in either the wet or dry season (2.06% and 2.30%). The annual evapotranspiration will not change significantly (2.18%) but the standard deviation will increase by 15.1%.

In the far future, it was found that the monthly mean maximum, minimum, and mean temperature will tend to increase in the wet season (May – October) by 2.34 °C, 2.41 °C and 2.40 °C and be especially high in May; and it will increase in dry season (November – April) by 2.95 °C, 2.79 °C and 2.91°C and be especially high in March. The mean of the annual maximum, minimum, and mean temperature will increase by 2.64 °C, 2.60 °C and 2.66 °C and the standard deviation will decrease -0.06, -0.04 and -0.06. While the seasonal evapotranspiration will increase in the wet and dry season (7.49% and 8.92%). The annual evapotranspiration will increase by 8.23% and standard deviation will increase by 5.03%.

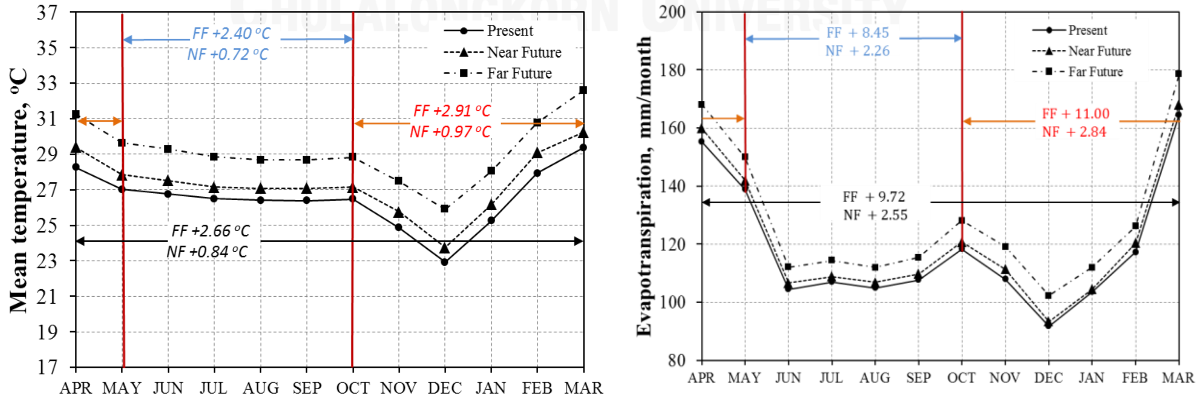
Table 5.12 Summary of seasonal mean and standard deviation of climate in Lower Nan River Basin

Climate	Season/ annual	Mean					Standard deviation				
		P	NF	Relative change	F	Relative change	P	NF	Relative change	F	Relative change
Maximum temperature, °C	Wet	29.96	30.61	0.65	32.31	2.34	0.27	0.24	-0.038	0.25	0.01
	Dry	31.58	32.60	1.02	34.52	2.95	0.68	0.93	0.25	0.57	-0.11
	Annual	30.77	31.60	0.83	33.41	2.64	0.40	0.55	0.15	0.34	-0.06
Minimum temperature, °C	Wet	24.33	25.00	0.67	26.74	2.41	0.20	0.21	0.02	0.24	0.04
	Dry	22.04	22.82	0.78	24.82	2.79	0.48	0.72	0.24	0.41	-0.07
	Annual	23.18	23.91	0.73	25.78	2.60	0.30	0.45	0.14	0.27	-0.04
Mean temperature, °C	Wet	26.59	27.31	0.72	28.99	2.40	0.23	0.26	0.03	0.23	0.00
	Dry	26.43	27.40	0.97	29.34	2.91	0.55	0.84	0.29	0.45	-0.10
	Annual	26.51	27.35	0.84	29.16	2.66	0.34	0.52	0.19	0.28	-0.06
Evapotranspiration, mm/month	Wet	681	695	2.06%	732	7.49%	4.5	4.5	0.00%	5.4	20.00%
	Dry	740	757	2.30%	806	8.92%	13.6	15.3	12.50%	13.8	1.47%
	Annual	1421	1452	2.18%	1538	8.23%	15.9	18.3	15.10%	16.7	5.03%

Remark : P = Present (1979 – 2006) , NF = Near future (2015 – 2039) and FF = Far future (2075 – 2099),
For temperature was calculated in difference: relative change for near future = NF – P; relative change for far future = FF – P,
For evapotranspiration was calculated in percentage: %relative change for near future = (NF-P)/P*100; %relative change for far future = (FF-P)/P*100



(a) Maximum temperature (b) Minimum temperature



(c) Mean temperature (d) Evapotranspiration

Figure 5.10 The monthly mean climate in Lower Nan River Basin

5.4.2 Trend of rainfall change

The study area for climate change assessment consists of the Upper, Middle and Lower Nan River Basin. The 64 observed rainfall stations were selected to represent these basins. (see the location details in Appendix A) The inverse distance weighted average method (IDW) was used to average the rainfall from the observed stations and the GCM grid points covered the entire Nan River Basin. The hybrid bias correction method was adopted to correct the bias of future MRI GCM precipitation. The rainfall change was evaluated using the statistical parameters in term of mean and standard deviation by comparing future periods with the present period.

The rainfall of the Upper Nan River Basin was averaged from the watershed of Sirikit Dam. The rainfall of the Middle Nan River Basin was averaged from the rainfall of Nam Pad (0912), Nan River Part 4 (0911) and Klong Tron sub basin (0913), respectively. The rainfall of the Lower Nan River Basin was averaged from Kwae Noi River (0914), Nam Phak (0915), Wang Thong River (0916), and the Lower Nan River (0917), respectively.

The change of rainfall in the concerned area included the Yom River Basin, the Wang River Basin, the Upper Ping River Basin, the Lower Ping River Basin, Sakaekang River Basin, and the Upper and Lower Chao Phraya River Basin as shown in Appendix B.2.

5.4.2.1 Upper Nan River Basin

The bias corrected rainfall in the near future (year 2015 – 2039) and far future (year 2075 – 2099) were compared to the present period (1979 – 2006) (shown in Table 5.13 and Figure 5.11). In the near future, it was found that the seasonal rainfall will tend to increase in both the wet and dry seasons (4.83% and 11.22%), but the monthly rainfall in November and December will tend to decrease 10.48% – 17.73% as shown in Figure 5.10. The annual rainfall average for the Upper Nan River Basin, which was computed as the mean of the annual rainfall, will increase by 5.82% compared with the present period. While in far the future, it was found that seasonal rainfall will tend to increase in both the wet and dry seasons

(10.34% and 13.28%), but the monthly rainfall will not change significantly, e.g. December (-0.83%). The annual rainfall will increase by 12.63% compared with the present period.

It was observed that the monthly rainfall for the near future will not change from the existing rainfall pattern; it will tend to increase in term of quantity only (+5.82%), while there will be a chance of seasonal shift in the peak rainfall pattern for the far future. The peak rainfall for the far future period will shift to August, while it occurs in September in the present period. A higher amount of rainfall will occur through the wet season (+20.78%). The variation of annual rainfall can be evaluated from the standard deviation (SD), it was found that the annual rainfall SD in near future will decrease but not significantly (-4.04%), but SD for the far future period it will decrease by 13.35%.

Table 5.13 Summary of seasonal mean and standard deviation of rainfall in Upper Nan River Basin

Month	Mean (mm)					Standard deviation				
	P	NF	%Diff	FF	%Diff	P	NF	%Diff	FF	%Diff
Wet	1020.6	1070.0	4.83	1134.3	11.14	146.6	150.2	2.52	136.5	-6.84
Dry	186.9	207.9	11.22	225.7	20.78	53.2	57.2	7.62	60.0	12.92
Annual	1207.5	1277.8	5.82	1360.1	12.63	154.6	148.3	-4.04	133.9	-13.35

Remark : P = Present (1979 – 2006) , NF = Near future (2015 – 2039) and FF = Far future (2075 – 2099)

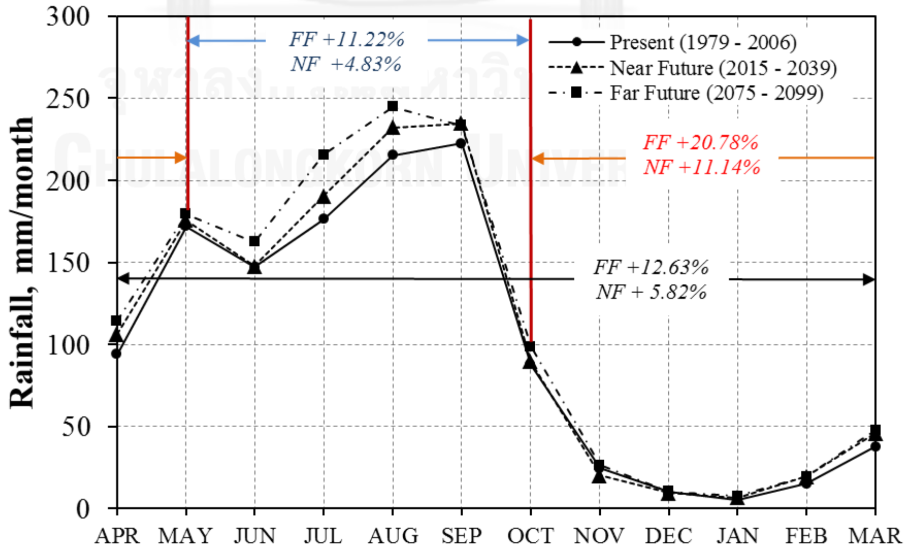


Figure 5.11 The monthly mean rainfall in Upper Nan River Basin

5.4.2.2 Middle Nan River Basin

The bias corrected rainfall for the year 2015 – 2039 was compared to the present period (1979 – 2006) (shown in Figure 5.12; Table 5.14). In the near future, it was found that the seasonal rainfall will increase not significantly in either of wet or dry season (4.52% and 5.74%), but the monthly rainfall in November and December will tend to decrease 16.39% – 32.06% as shown in Figure 5.12. The annual rainfall average for the Middle Nan River Basin, which was computed as the mean of the annual rainfall, will increase by 4.30% compared with the present period; on the other hand, in the far future, it was found that the monthly rainfall will tend to increase in both the wet and dry season (10.34% and 13.28%), but the monthly rainfall will not change significantly (change less than 5%) in March. (-0.83%). The annual rainfall will increase by 10.36% compared with the present period.

It was observed that the monthly rainfall for the near future will not change from the existing rainfall pattern; it will tend to increase in term of quantity, except in May when it increases by 12.73%. In the far future, the higher amount of rainfall will occur though the wet season. The variation of annual rainfall can be evaluated from the standard deviation, and it was found that the annual rainfall SD in the near future will not change significantly (change less than 5%) (-1.20%), but for the SD of far future period it will decrease by 12.85%.

Table 5.14 Summary of seasonal mean and standard deviation of rainfall in Middle Nan River Basin

Month	Mean					Standard deviation				
	P	NF	%Diff	FF	%Diff	P	NF	%Diff	FF	%Diff
Wet	976.9	1021.0	4.52	1077.9	10.34	147.3	158.9	7.83	139.2	-5.52
Dry	170.7	180.5	5.74	193.4	13.28	57.2	45.7	-20.07	49.0	-14.33
Annual	1152.0	1201.6	4.30	1271.3	10.36	159.1	157.2	-1.20	138.7	-12.85

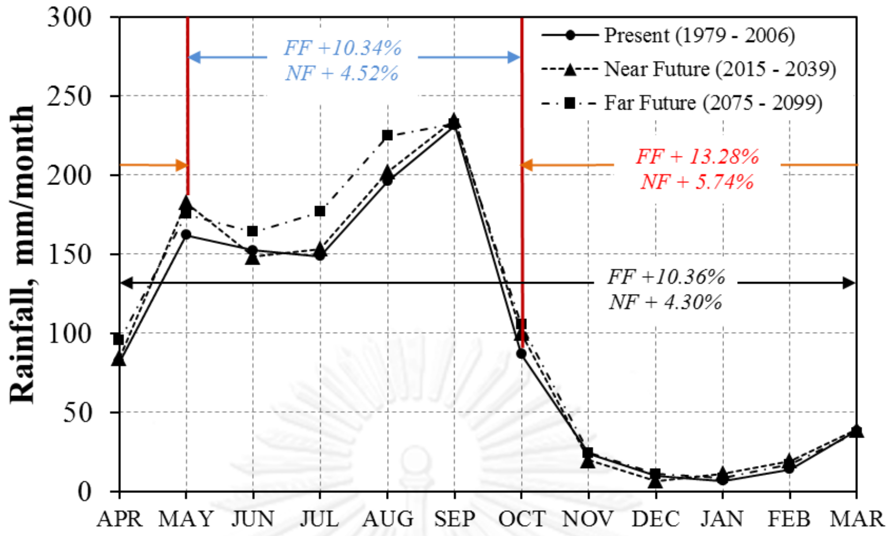


Figure 5.12 The monthly mean rainfall in Middle Nan River Basin

5.4.2.2 Lower Nan River Basin

The bias corrected rainfall for the year 2015 – 2039 was compared to the present period (1979 – 2006) (shown in Figure 5.13; Table 5.15). In the near future, it was found that the seasonal rainfall will increase not significantly in either the wet or dry season (5.46% and 4.62%), but the monthly rainfall in November, December and March will tend to decrease 11.35% – 16.56% as shown in Figure 5.13. The annual rainfall of the Lower Nan River Basin will increase not significantly (4.97%), while in the far future, it was found that the seasonal rainfall will tend to increase in both the wet and dry seasons (10.69% and 12.08%), but the monthly rainfall will decrease in March (-10.37%). The annual rainfall will increase by 10.57% compared with the present period.

It was observed that the monthly rainfall for the near future will not change from the existing rainfall pattern; it will tend to increase in term of quantity only; especially more rain in May, while there will be a chance of seasonal shift in the rainfall pattern in the far future. The peak rainfall for the far future period will shift to August, while it occurs in September in the present period. The higher amount of rainfall will occur though the wet season. The variation of annual rainfall can be evaluated from the standard deviation, and it was found that annual rainfall SD in the near future will decrease by 14.13%, but the SD for the far future period it will decrease by 42.73%.

Table 5.15 Summary of seasonal mean and standard deviation of rainfall in Lower Nan River Basin

Month	Mean					Standard deviation				
	P	NF	%Diff	FF	%Diff	P	NF	%Diff	FF	%Diff
Wet	1009.4	1064.5	5.46	1117.3	10.69	200.2	180.0	-10.09	109.6	-45.27
Dry	211.4	221.1	4.62	236.9	12.08	59.0	54.5	-7.59	59.8	1.35
Annual	1224.8	1285.6	4.97	1354.2	10.57	201.3	172.8	-14.13	115.3	-42.73

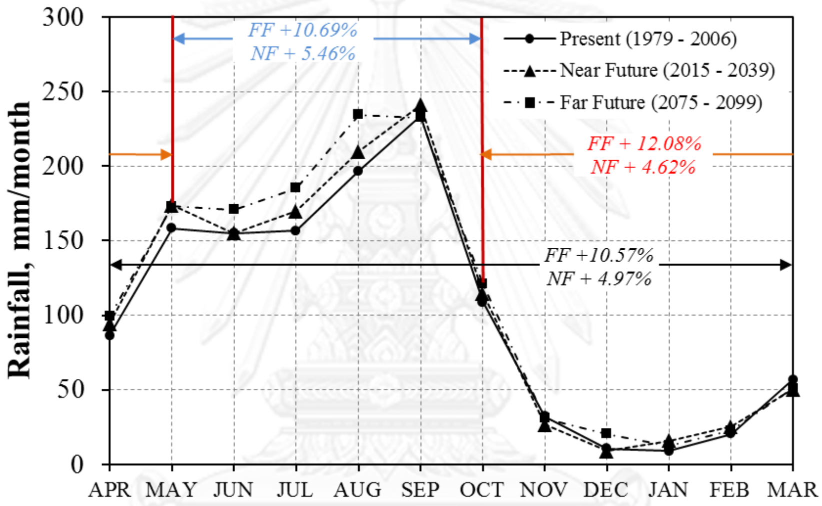


Figure 5.13 The monthly mean rainfall in Lower Nan River Basin

The change of the rainfall in the concerned area includes the Yom River Basin, the Wang River Basin, the Upper and Lower Ping River Basin, the Upper Chao Phraya River Basin and the Sakaekang River Basin, as shown in Appendix B.1.2.

5.5 Trend of water demand change

The irrigation water demand was estimated from difference of the effective rainfall and evapotranspiration, which followed Eq. 15 – 16 in Chapter 4. The irrigation water demand rate was set as the default values which incorporated the water decision making module. In this chapter, the irrigation water demand rate was estimated by calculating the water demand per 1,000 rais.

For the change evaluation, the irrigation water demand rate in the near future (year 2015 – 2039) and far future (year 2075 – 2099) was compared to the present period (1979 – 2006). The irrigated areas in this study focused on 2 main irrigation projects which received the allocated water directly from Sirikit Dam and Bhumibol Dam; they included the Phitsanulok Irrigation Project (PSK) and the Chao Phraya Irrigation Project (CHY). Hence, the Phitsanulok Irrigation Project (PSK) would use the related input variables from the Lower Nan River Basin, while the Chao Phraya Irrigation Project (CHY) would use the related input variables from Lower Chao Phraya River basin. Therefore, the change in water demand was evaluated according to each local climate condition.

5.5.1 Phitsanulok Irrigation Project

In the near future, the results showed that the water demand of rice (per 1000 rais) will decrease -4.40% in the wet season and less water demand will occur in June by -8.14% due to more rainfall. The water demand in dry season will fluctuate slightly, especially decreasing in November by -4.52% and increasing in January 7.99% (as shown in Figure 5.14a). The annual water demand of rice will increase not significantly (less than 5%; 1.42%) (as shown in Table 5.16).

In the far future, the results show that the water demand of rice will tend to decrease -7.7% in the wet season, and especially less water demand will occur in August and September, when it will decrease by -7.34% and -8.82% respectively; on the other hand, the water demand in the dry season will tend to increase +11.2% especially in January by 11.47% (as shown in Figure 5.14a). The water demand for crops in the near and far future is shown in Figure 5.14b. The annual water demand of rice will not change significantly (change less than 5%; 3.59%) (as shown in Table 5.16).

Although the near and far future evapotranspiration will increase in both the wet and dry season, the increase in the effective rainfall in the wet season will cause the water demand to decrease (see Table 5.16). On the other hand, the decrease in the effective rainfall in the dry season will cause the water demand increase. The trend of the upland crop water demand are also similar to the paddy’s.

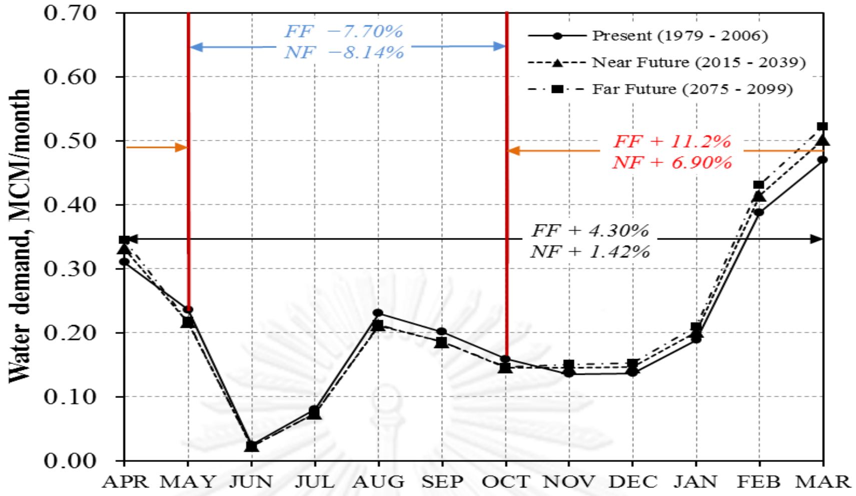
Table 5.16 Summary of the seasonal mean water demand (per 1000 rais) of Phitsanulok Irrigation Project

a) Paddy

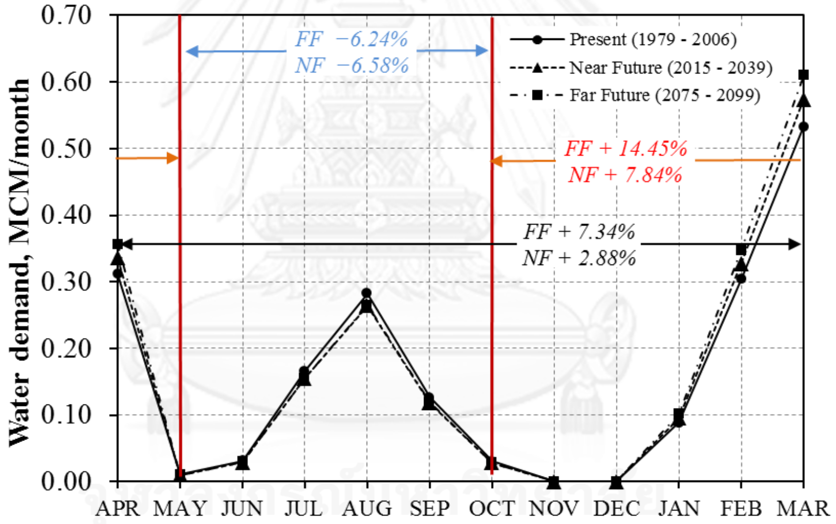
Variable	Season/annual	Mean					Standard deviation				
		P	NF	%Diff	FF	%Diff	P	NF	%Diff	FF	%Diff
Evapotran-spiration, mm	Wet	681	695	1.99	732	7.43	4.52	4.49	-0.66	5.33	17.8
	Dry	740	757	2.31	806	8.87	13.6	15.3	12.7	13.8	1.23
	Annual	1421	1452	2.16	1538	8.18	15.9	18.3	15	16.7	5.15
Effective rainfall, mm	Wet	723	747	3.29	770	6.46	19.2	18.9	-1.4	18	-6
	Dry	196	185	-5.42	187	-4.55	25.8	28	8.2	28.5	10.2
	Annual	919	932	1.44	957	4.11	50.8	53.9	6.23	55.6	9.5
Water demand, MCM	Wet	0.93	0.86	-8.14	0.85	-7.7	0.09	0.07	-19.79	0.06	-30.1
	Dry	1.63	1.74	6.90	1.81	11.2	0.14	0.15	7.36	0.16	14.5
	Annual	2.56	2.60	1.42	2.67	4.3	0.13	0.14	11.03	0.14	11.0

b) Upland crop

Variable	Season/annual	Mean					Standard deviation				
		P	NF	%Diff	FF	%Diff	P	NF	%Diff	FF	%Diff
Evapotran-spiration, mm	Wet	681	695	1.99	732	7.43	4.52	4.49	-0.66	5.33	17.8
	Dry	740	757	2.31	806	8.87	13.6	15.3	12.7	13.8	1.23
	Annual	1421	1452	2.16	1538	8.18	15.9	18.3	15	16.7	5.15
Effective rainfall, mm	Wet	723	747	3.29	770	6.46	19.2	18.9	-1.4	18	-6
	Dry	196	185	-5.42	187	-4.55	25.8	28	8.2	28.5	10.2
	Annual	919	932	1.44	957	4.11	50.8	53.9	6.23	55.6	9.5
Water demand, MCM	Wet	0.65	0.60	-6.58	0.61	-6.24	0.11	0.08	-24.1	0.11	4.3
	Dry	1.24	1.33	7.84	1.41	14.45	0.21	0.24	12.9	0.25	17.6
	Annual	1.88	1.94	2.88	2.02	7.34	0.17	0.19	13.11	0.20	19.1



(a) Rice



(b) Crop

Figure 5.14 The monthly mean water demand (per 1000 rais) of Phitsanulok Irrigation Project

5.5.2 Chao Phraya Irrigation Project

In the near future, the results showed that the water demand of rice will decrease -4.55% in the wet season and less water demand will occur in June with a decrease of 14.32%. The water demand in the dry season will increase 8.18% and fluctuate slightly especially decreasing in November by -6.07% and increasing in January 14.11% (as show in Figure 5.15a). The standard deviation of the seasonal water demand will tend to decrease -2.45% in the wet season and increase +33.11% in dry season.

In the far future, the water demand of paddy will tend to decrease -7.47% in the wet season, and especially less water demand will occur in August and September with a decrease of -11.59% and -13.93%. On the other hand, the water demand of paddy in the dry season will tend to increase 10.43% and especially in January by 17.47% (as shown in Figure 5.15a). The standard deviation of the seasonal water demand will tend to decrease -5.43% in the wet season and increase 35.89% in the dry season. The water demand for upland crops (per 1000 rais) showed similar trend as paddy's through the same months in the near and far future shown in Figure 5.15b.

Although the near future evapotranspiration will increase in the wet season, the increasing effective rainfall will cause the water demand to decrease (see Table 5.17). On the other hand, the evapotranspiration will tend to decrease but the effective rainfall in the dry season will tend to decrease in a greater amount, which will cause the water demand to increase.

However the far future evapotranspiration will increase in both the wet and dry season, but the increasing effective rainfall in the wet season will cause the water demand to decrease (see Table 5.17). On the other hand, the decreasing effective rainfall in the dry season will cause the water demand to increase.

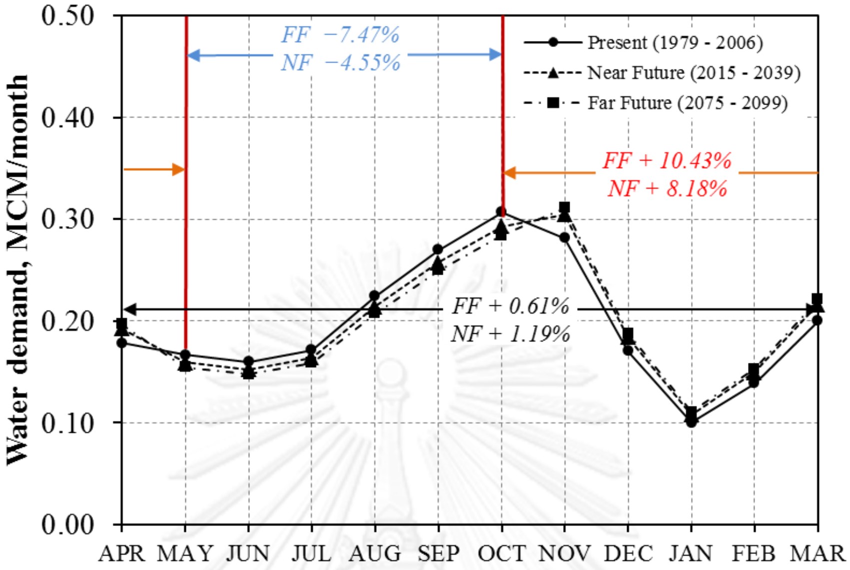
Table 5.17 Summary of the seasonal mean water demand (per 1000 rais) of Chao Phraya Irrigation Project

a) Paddy

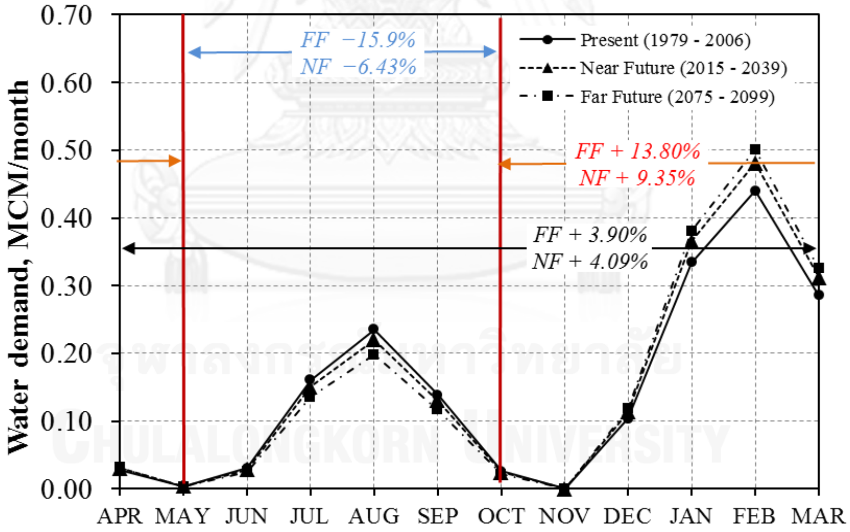
Variable	Season/annual	Mean					Standard deviation				
		P	NF	%Diff	FF	%Diff	P	NF	%Diff	FF	%Diff
Evapotran-spiration, mm	Wet	757	796	5.13	867	14.5	5.2	9.92	90.8	10.1	94.9
	Dry	740	718	-2.96	826	11.6	13.4	10.5	-22.2	16.5	22.9
	Annual	1478	1562	5.68	1669	12.9	104	28.8	-72.3	118	14.1
Effective rainfall, mm	Wet	665	722	8.57	791	18.9	19.1	24.1	26.6	12.3	-35.2
	Dry	177	126	-28.5	151	-14.3	24.6	22.8	-7.35	28.3	14.9
	Annual	842	848	0.80	942	12	47.4	53.3	12.4	59.4	25.4
Water demand, MCM	Wet	1.30	1.24	-4.55	1.20	-7.47	0.06	0.059	-2.45	0.057	-5.43
	Dry	1.07	1.16	8.18	1.18	10.43	0.05	0.067	33.11	0.068	35.89
	Annual	2.37	2.40	1.19	2.38	0.61	0.07	0.060	-14.00	0.060	-14.70

b) Upland crop

Variable	Season/annual	Mean					Standard deviation				
		P	NF	%Diff	FF	%Diff	P	NF	%Diff	FF	%Diff
Evapotran-spiration, mm	Wet	757	796	5.13	867	14.5	5.2	9.92	90.8	10.1	94.9
	Dry	740	718	-2.96	826	11.6	13.4	10.5	-22.2	16.5	22.9
	Annual	1478	1562	5.68	1669	12.9	104	28.8	-72.3	118	14.1
Effective rainfall, mm	Wet	665	682	2.51	791	18.9	19.1	24.1	26.6	12.3	-35.2
	Dry	177	126	-28.5	151	-14.3	24.6	22.8	-7.35	28.3	14.9
	Annual	842	808	-3.99	942	12	47.4	53.3	12.4	59.4	25.4
Water demand, MCM	Wet	0.60	0.56	-6.43	0.50	-15.9	0.09	0.08	-2.37	0.07	-12.3
	Dry	1.19	1.30	9.35	1.36	13.8	0.19	0.19	4.11	0.21	8.4
	Annual	1.79	1.86	4.09	1.86	3.9	0.17	0.15	-3.71	0.17	0.3



(a) Rice



(b) Crop

Figure 5.15 The monthly mean water demand (per 1000 rais) of Chao Phraya Irrigation Project

5.6 Trend of runoff change

The runoff data for the change evaluation in this study were derived from the simulated runoff results of the HEC-HMS rainfall-runoff model. The rainfall-runoff model was calibrated and verified with the observed runoff data. This study attempted to develop the runoff parameter functions based on the monthly rainfall pattern. First, the rainfall-runoff model was simulated year by year to calibrate the runoff parameter for 1990 - 2007. In this process, the univariate gradient optimization method was used to find the suitable parameters for each year. The goodness of fit test of model calibration shows the correlation of the determination (R^2) is 0.61, the root mean square error (RMSE) and standard error (SE) at 0.61 – 0.85 and 36.22 – 174.60, respectively (see Table B-1). The details of the runoff patternization and estimation are shown in Appendix B.3.1 – B.3.8.

Second, the runoff parameter functions were formulated from the relationship between the accumulative rainfall and runoff parameter. The runoff parameter includes the initial abstraction (Int), Curve number (CN) Storage Clark number (Sc) which matched 5 rainfall patterns (see Figure B.12). In this step, the runoff parameter functions were validated by re-simulating the runoff in 1990 – 2007. The goodness of fit test of the model calibration shows that the correlation of the determination (R^2) was 0.66 – 0.88, and the root mean square error (RMSE) and standard error (SE) were 31.68 – 173.35 and 14.80 – 121.08, respectively (see details in Table B.2).

The model validation was the final step to check the reliability of the rainfall-runoff model; according to the mostly observed runoff data were recorded only in year 1990 – 2006, but the inflows of Sirikit Dam were recorded from 1975 to the present. Consequently, the model validation step would simulate the runoff for the 1979 – 1989, and then the simulated runoff results would be compared with the observed inflow of Sirikit Dam. The goodness of fit test of the model calibration shows that the correlation of the determination (R^2) was 0.82, and the root mean square error (RMSE) and standard error (SE) were

87.74 and 82.38, respectively (see details in Table B.3). The results show that the rainfall-runoff model can simulate the inflow of Sirikit Dam and the lateral flow of Nan River Basin reasonably.

Regarding the runoff simulation with the GCM rainfall, the runoff parameter functions were applied with the bias-corrected GCM rainfall. The runoff results would be used to study future changes and provide an input variable for the reservoir operation model. The runoff simulation periods included the present period (1979 – 2007), the near future period (2015 – 2039) and the far future period (2075 – 2099). The change evaluation for the near and far future runoffs, was compared with the present period (1979 – 2007).

Regarding a clear view of the change evaluation for the Nan River Basin, the runoff study area was separated into 3 parts: the inflow of Sirikit Dam and the side flows of the middle and lower Nan River Basin. The inflow of Sirikit Dam is the runoff of the watershed of Sirikit Dam or the Upper Nan River Basin over Sirikit Dam. The sideflows of the Middle Nan River Basin were grouped from the sideflow of SF-01, SF-02 and SF-03, respectively. The sideflows of the Lower Nan River Basin were grouped from the sideflows in SF-04, SF-05, SF-06, SF-07 and SF-08, respectively (see the flowchart of the river basin network in Figure B.15). Mean and probability of sideflows were used to analyze the change in the sideflow of the sub-basins as shown in Figure C.1 to C.5.

5.6.1 Trend of inflow change

In the near future, the results show that the inflow will increase 6.43% in the wet season and a higher inflow will occur at the end of the wet season in September and will increase 6.43%. The inflow in the dry season will increase (+0.74%) and fluctuate slightly, especially decreasing to the lowest in November by -6.63% and increasing in March by 18.47% (as shown in Figure 5.16). The standard deviation of the monthly inflow will tend to decrease by -10.54% in wet season and increase +2.58% in the dry season.

In the far future, the inflow will tend to increase 12.64% in wet season and especially more inflow will occur in July, August and September, with a higher peak in September, while the inflow in the dry season tends will increase 7.55% and especially in January by 29.33% (as shown in Figure 5.16). The bias corrected GCM rainfall in the Upper Nan River Basin tend to increase in wet season that causes the inflow to increase. Furthermore, the peak of rainfall in Upper Nan River Basin shift to August (see Figure 5.11) that causes the inflow to increase in August but the peak of inflow still in September. The standard deviation of monthly inflow will decrease 10.54% in wet season and increase 2.58% in dry season.

Table 5.18 Summary of the seasonal mean inflow of Sirikit Dam

Month	Mean					Standard deviation				
	P	NF	%Diff	FF	%Diff	P	NF	%Diff	FF	%Diff
Wet	5189.2	5523.2	6.43	5845.0	12.64	1166.9	1023.0	-12.33	1043.9	-10.54
Dry	839.1	845.3	0.74	902.5	7.55	225.1	185.9	-17.42	230.9	2.58
Annual	6028.3	6368.5	5.64	6747.5	11.93	1240.1	1096.0	-11.62	962.2	-22.41

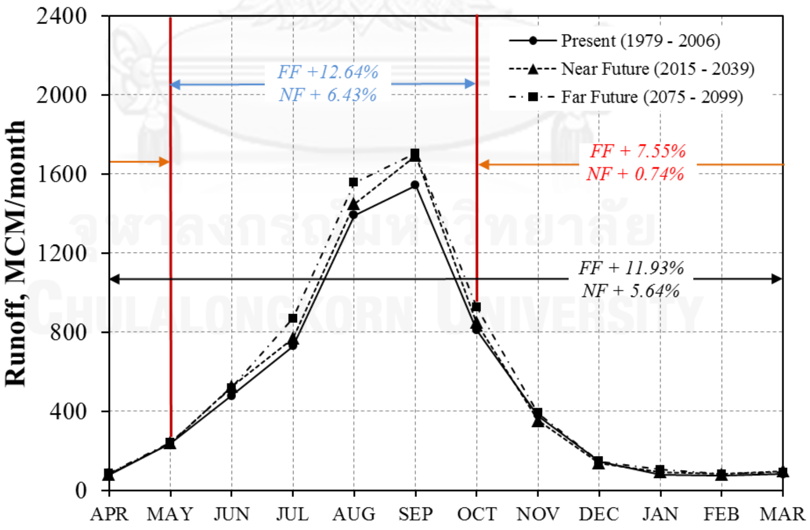


Figure 5.16 The monthly mean inflow of Sirikit Dam

5.6.2 Trend of lateral flows change

5.6.2.1 Trend of lateral flows of Middle Nan River Basin

In the near future, the results show that the lateral flows will increase 3.69% in wet season and the higher lateral flows will occur in the in May and October by increasing 13.07% and 11.40%. It was found that the peak of lateral flows still occur in September but more volume in August. The lateral flow in dry season will fluctuate slightly especially lowest decrease in December -15.22% and increase in January 27.16% (as show in Figure 5.17). The bias corrected GCM rainfall of Middle Nan River Basin will tend to increase in the dry season (see Figure 5.12) that causes the lateral flow to increase. The standard deviation of the seasonal lateral flow will tend to decrease -49.31% in the wet season and increase by 19.24% in the dry season.

In the far future, the lateral flows will tend to increase by 7.96% in the wet season, and especially a greater lateral flow will occur in July and October with an increase of 14.12% and 17.14%, while the side flow in the dry season will tend to increase by 9.82%, and especially in January by 15.47% (as shown in Figure 5.17). The bias-corrected GCM rainfall in the Middle Nan River Basin will tend to increase in the wet season that induced the lateral flow increase. The standard deviation of the seasonal lateral flow will decrease by 18.71% in the wet season and increase by 17.41% in the dry season.

Table 5.19 Summary of the lateral flow of Middle Nan River Basin

Month	Mean					Standard deviation				
	P	NF	%Diff	FF	%Diff	P	NF	%Diff	FF	%Diff
Wet	2064.7	2141.0	3.69	2229.0	7.96	842.9	427.3	-49.31	685.2	-18.71
Dry	921.4	956.3	3.79	1011.9	9.82	304.8	363.4	19.24	357.8	17.41
Annual	2986.1	3097.3	3.72	3240.9	8.53	1075.9	461.2	-57.13	710.6	-33.95

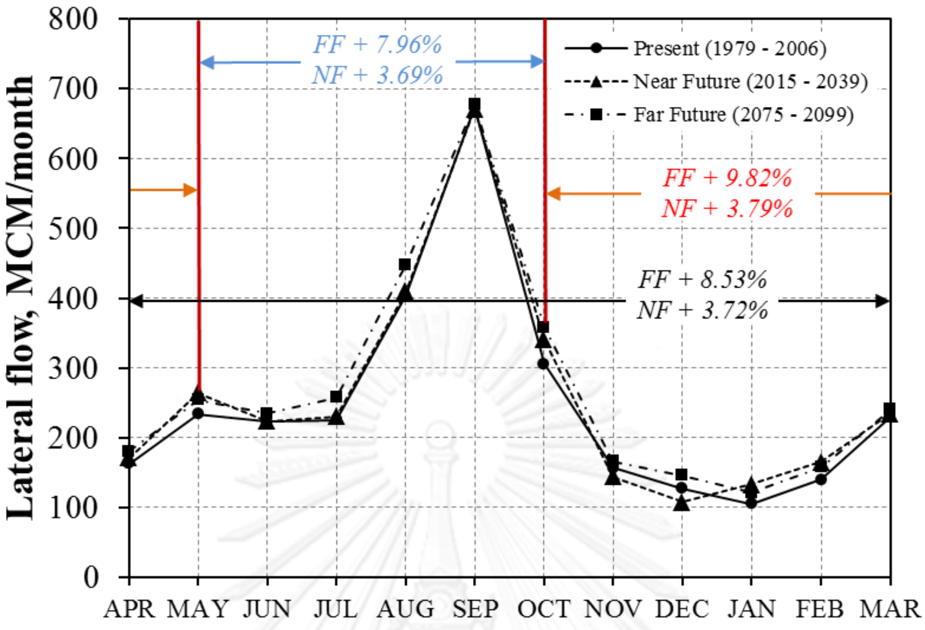


Figure 5.17 The monthly mean lateral flows of Middle Nan River Basin

5.6.2.2 Trend of lateral flow in Lower Nan River Basin

In the near future, the results show that the lateral flow will increase 4.75% in the wet season and a higher lateral side flow will occur in May and July with an increase of 7.99% and 11.28% (conform with rainfall pattern in Figure 5.13). The lateral flow in the dry season will fluctuate slightly, and be especially lowest in December -3.13% with an increase in January of 27.91% (as shown in Figure 5.18). The bias-corrected GCM rainfall (see Figure 5.13) in the Lower Nan River Basin will tend to increase in the dry season that induced the lateral flow increase. The standard deviation of the seasonal lateral flow will tend to decrease -17.40 in the wet season and -24.02% in the dry season.

In the far future, the lateral flow will tend to increase 7.27% in the wet season, and especially a greater lateral flow will occur in July and August, with an increase of 17.66% and 11.65%, while the lateral flow in the dry season will tend to increase by 12.71%, and especially in December by 37.11% (as shown in Figure 5.18). The bias-corrected GCM rainfall in the Lower

Nan River Basin will tend to increase in the wet season that causes the lateral flow to increase. The standard deviation of the seasonal lateral flow will tend to decrease -12.03% in the wet season and -29.53% in the dry season.

Table 5.20 Summary of the lateral flow of Lower Nan River Basin

Month	Mean					Standard deviation				
	P	NF	%Diff	FF	%Diff	P	NF	%Diff	FF	%Diff
Wet	6838.7	7163.8	4.75	7336.0	7.27	2964.6	2448.8	-17.40	2607.9	-12.03
Dry	3658.1	3758.4	2.74	4122.9	12.71	1641.5	1247.2	-24.02	1156.8	-29.53
Annual	10496.8	10922.2	4.05	11458.9	9.17	3895.2	3204.0	-17.74	2970.3	-23.75

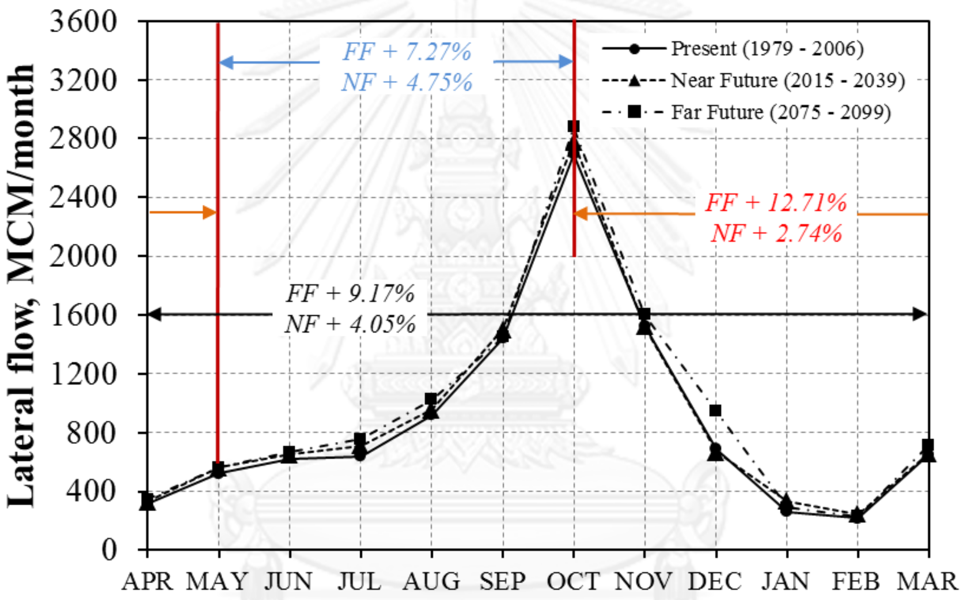


Figure 5.18 The monthly mean lateral flow of Lower Nan River Basin

The change of the runoff in the concerned area includes the Yom River Basin, the Wang River Basin, the Upper and Lower Ping River Basin, the Upper Chao Phraya River Basin and the Sakaekang River Basin, as shown in Appendix B.2. It was found that the lateral flow from the concerned area will tend to increase in both wet and dry season. The peak of lateral flow of Yom River Basin will be higher in October and more volume will occur in September in both near and far future (see Figure B.9).

5.7 Summary of the change in the hydrological variables

The quantitative in terms of change in temperature, rainfall, water demand and runoff for the Nan River Basin is summarized in this section.

5.7.1 Climate

- The annual maximum temperature will increase in both the near and far future (+0.79 to +0.83 °C and +2.47 to +2.64°C).

- The annual minimum temperature will increase in both the near and far future (+0.69 to +0.73 °C and +2.51to +2.60°C).

- The annual mean temperature will increase in both the near and far future (+0.81 to +0.84 °C and +2.54 to +2.66°C).

- The annual evapotranspiration will not change significantly in the near future (+2.18%) but it will increase in the far future (+8.07% to +8.23%)

Table 5.21 Change in the climate of the Nan River Basin

Area	Variable	Change in near future			Change in far future		
		Wet	Dry	Annual	Wet	Dry	Annual
Upper Nan	Maximum temperature, °C	+0.66	+0.93	+0.79	+2.3	+2.64	+2.47
	Minimum temperature, °C	+0.66	+0.72	+0.69	+2.4	+2.61	+2.51
	Mean temperature, °C	+0.72	+0.91	+0.81	+2.37	+2.71	+2.54
	Evapotranspiration, %	+2.11	+2.25	+2.18	+7.52	+8.58	+8.07
Lower Nan	Maximum temperature, °C	+0.65	+1.02	+0.83	+2.34	+2.95	+2.64
	Minimum temperature, °C	+0.67	+0.78	+0.73	+2.41	+2.79	+2.60
	Mean temperature, °C	+0.72	+0.97	+0.840.	+2.40	+2.91	+2.66
	Evapotranspiration, %	+2.06	+2.30	+2.18	+7.49	+8.92	+8.23

5.7.2 Rainfall

- The annual rainfall of the Nan River Basin and concerned area will increase in the both near and far future as shown in Table 5.22.

- The monthly rainfall for the near future will not change from the existing rainfall pattern; it will tend to increase in term of quantity only.

- Regarding the upper and Lower Nan River Basin, there will be a chance of seasonal shift in the rainfall pattern in the far future. The peak rainfall for the far future period will shift to August, while it will occur in September for the present period. The higher amount of rainfall will occur during the wet season.

Table 5.22 Change in rainfall of Nan River Basin and concerned area

Area	Change in near future (%)			Change in near future (%)		
	Wet	Dry	Annual	Wet	Dry	Annual
Upper Nan	4.83	11.22	5.82	11.14	20.78	12.63
Middle Nan	4.52	5.74	4.3	10.34	13.28	10.36
Lower Nan	5.46	4.62	4.97	10.69	12.08	10.57
Yom River Basin	1	-6.78	-0.21	7.6	2.35	6.91
Wang River Basin	1.75	-10.24	-0.14	8.29	1.41	7.59
Upper Ping River Basin	8.13	57.8	14.33	11.67	61.29	17.59
Lower Ping River Basin	-0.75	-5.93	-1.52	5.4	4.44	5.67
Upper chao Phraya River Basin	1.72	3.18	2.02	8.63	8.37	8.58
Lower chao Phraya River Basin	11.53	-27.63	4.73	34.39	-12.64	26.09
Sakaekang River Basin	1.26	3.03	1.59	4.49	3.2	4.25

5.7.3 Water demand rate

- The annual water demand (per 1000 rais) of both irrigation projects will not change significantly in either the near or far future as shown in Table 5.23.

- The water demand in the dry season will be higher than in the wet season in both the near and far future.

Table 5.23 Change in water demand rate of Phitsanulok and Chao Phraya Irrigation Project

Irrigation Project	Crop	Change in near future			Change in far future		
		Wet	Dry	Annual	Wet	Dry	Annual
PSK	Paddy	-8.14	+6.90	+1.42	-7.7	+11.2	+4.30
	Upland crop	-6.58	+7.84	+2.88	-6.24	+14.45	+7.34
CHY	Paddy	-4.55	+8.18	+1.19	-7.47	+10.43	+0.61
	Upland crop	-6.43	+9.35	+4.09	-15.9	+13.80	+3.90

Remark : PSK = Phitsanulok irrigation project, CHY = Chao Phraya irrigation project

5.7.4 Inflow and lateral flow

- The annual runoff of the Nan River Basin for the near future will not change significantly, while that for the far future will increase as shown in Table 5-24.

- The monthly inflow of Sirikit Dam and the Lower Nan River Basin for the near and far future periods will not change from the existing runoff pattern; it will tend to increase in term of quantity only.

- The higher monthly lateral flow of the Middle Nan River Basin will occur in the early rainy season; however, the runoff pattern will tend to increase in terms of quantity only.

Table 5-24 Change in runoff of Nan River Basin and concerned areas

Area	Change in near future (%)			Change in far future (%)		
	Wet	Dry	Annual	Wet	Dry	Annual
Upper Nan	6.43	0.74	5.64	12.64	7.55	11.93
Middle Nan	3.69	3.79	3.72	7.96	9.82	8.53
Lower Nan	4.75	2.74	4.05	7.27	12.71	9.17
Yom River Basin	20.92	3.02	17.22	28.74	6.51	23.39
Wang River Basin	17.63	22.5	19.32	31.27	36.47	33.11
Upper Ping River Basin	8.17	16.62	9.8	14.81	16.8	15.15
Lower Ping River Basin	4.05	31.52	11.35	9.97	43.4	21.04
Upper chao Phraya River Basin	1.00	13.39	2.96	16.15	31.21	18.54
Sakaekang River Basin	1.34	5.96	1.87	7.04	1.73	6.43

CHAPTER VI

IMPACT ASSESSMENT ON EXISTING RESERVOIR OPERATION

The impact assessment on existing reservoir operations is to assess the storage and release changes, water demand, water deficit, spillage and accumulative runoff. In this study, the dam operation included 2 operation rules: 1) the general dam operation rule and 2) the flood dam operation rule. General dam operation was improved by introduction of the probability decision tree method, combined with the release – storage ratio (RSR) method. The release rules were derived from the proportion between release and antecedent effective storage (the general reservoir operation model development procedures are shown in Appendix D).

The impact assessment periods were separated into 3 periods according to the GCM climate data: 1) present in 1979 – 2006 (P); 2) near future in 2015 – 2039 (NF); and 3) near future in 2075 – 2099 (FF), respectively. The input variables for both dam operation models included the initial storage, estimated inflow and lateral flows, bias corrected GCM rainfall, water demand rate. Furthermore the dam's physical characteristics were considered in the dam operation model such as height – volume – area curve and existing reservoir operation rule, etc. Therefore, the propose of this chapter is to provide the impact assessment results in order to identify the effect of the climate change and to indicate how to adjust the dam operations against the water deficit and flood problems in the present climate condition. The impact assessment factors in this study were considered in relation to water demand, reservoir water balance, spillage, water deficit, seasonal runoff, and accumulative runoff at the control points (see Figure F.1). The water deficit was calculated from the water allocation minus the water demand of each project. The water allocation of the Phitsanulok Irrigation Project (PSK) was calculated from the water allocation ratio multiplied by the stream flow at N.60 and lateral flow SF-03. The water allocation ratio of the Phitsanulok Irrigation Project (PSK) is shown in Table F.1 (see details in Figure F.1).

6.1 Existing reservoir operation system development

The existing reservoir operation system in this study is composed of 4 modules, i.e. 1) the reservoir operation module; 2) the water release decision making module; 3) the water demand decision making module; 4) the water network balance module (see details in Appendix F). The components of the existing reservoir operation and the data transferring process are shown Figure 6.1. The detail of the existing reservoir operation system is as follows.

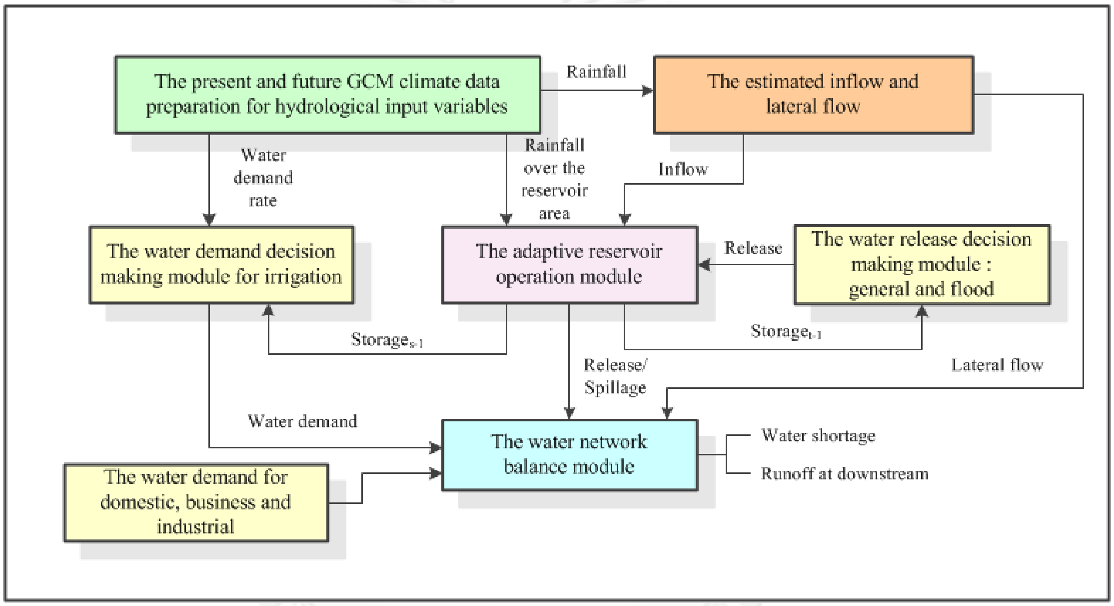


Figure 6.1 The components of the existing reservoir operation and the data transferring process

6.1.1 Reservoir operation module

The reservoir operation module is to balance the storage in the reservoir by using reservoir water balance equation. The input variables included rainfall, maximum and minimum temperature, relative humidity, initial storage, inflow and the reservoir characteristics, such as height – volume – area curve, crest of spillway, maximum storage level, normal storage level, dead storage level and reservoir rule curve. The function of reservoir operation model is to integrate the water release decision making module and the water demand decision making module to compute the water storage and release.

The reservoir operation system can carry out follow this processes shown in Figure 6.1. First, the user set up the initial storage (S_{t-1}) which use as the input in the reservoir release rule. The water demand decision module will use the initial storage to decide selecting the crop cultivation area for planting in this season. For example, the initial storage located in wet season, normal type and high level. The water demand decision module will select the crop cultivation area equal to 648,294 rais (see Table D.4). And then the program will take this area to multiple with water demand rate before sending to reservoir release rule. The program will take S_{t-1} to select the release-effective storage ratio. For example, if the initial effective storage is equal to 2,326 MCM, this value locates in the wet season and normal type in May. Next, the program will select the normal wet ratio (0.23) to calculate (see Table D.2). Next, normal wet ratio will calculate the water release equal to 535.04. Next, the reservoir release module will send the release value to the reservoir operation model for analyzing the water balance in the reservoir. Thus, the reservoir operation module will analyze the water balance by calculating the storage in present. The overflow of reservoir will be calculated in the case of the inflow make the storage value higher than the overflow level. This overflow water will be accounted to the release before flowing to downstream. The release will be the input variable for the water network balance model. This process will continue calculating entire 1 season or 6 months. And then the program will send the storage at the end of season to the water demand decision making module for the new calculating loop. Therefore, this reservoir operation module will analyze in one season for one looping after that the storage at the end of season will select the new crop requirement for the next looping. So the concept of water demand decision making module will carry out in one season while the water release decision making module will decide to release in every month or month per month.

6.1.2 Water release decision making module

The release decision making module is a module for dam water release to downstream. This release decision-making module uses the release rules from the release–storage ratio (RSR). For the general reservoir operations, the release rule was patterned from the effective storage in each water season and each month within the season by using the probability decision tree method and classified to be high, normal, dry and very dry water season (see Figure D.4). Furthermore the monthly water release can be separated into sub level such as higher, high, medium, low and lower. The release-effective storage ratio (r_i) was analyzed from the proportion between monthly water release in the present month (O_t) and antecedent effective storage (Se_{t-1}). Thus, the average monthly release-effective storage ratio was grouped according to the seasonal water condition and monthly antecedent effective storage level. The amount of water release in the present month (R_t) can be calculated by taking the antecedent effective storage (Set-1) and multiplying with this release-effective storage ratio (see Eq. (1) in Appendix D.1.5). The release–effective storage ratio of Sirikit Dam is shown in Table D-2. The flood dam operation generated the release rules by adopting the release plan in 2012 from the RID regulation plan (RID, 2012) and turn to release-storage ratio as in the case of general reservoir operation rule.

6.1.2.1 General reservoir operation rule

General reservoir operation rule is set up from the ratio of water release and the previous 1 month of storage. For the ratio generation, the release and effective storage in the past record in year 1979 – 2011 was used as the baseline. The concept of this general rule is assumed that the reservoir operator release the water according to the water season. The water season can be classified by probability of effective storage in previous 1 month (S_{t-1}) shown as Figure D.4. For example, if the effective storage of previous 1 month of May equal to 4,088 that locates in wet and normal season; the sub level is medium. The ratio of release and effective storage will be 0.23 (see Table D.2); and then the release can be calculated by taking this ratio to multiple with effective storage of previous 1 month (S_{t-1}). Hence, the release will vary according to the effective storage.

The general reservoir operation model developed was validated by comparing the observed release data with the computed release data. The model calibration and verification periods were for 1987 to 1996 and 1997 to 2011 respectively. In the model calibration, the correlation (R^2) and the root mean square error of water release of Sirikit Dam were found to be good at 0.74 and 166 MCM, respectively. On the other hand in the model verification, the correlation (R^2) and the root mean square error of release were found to be good at 0.80 and 145 MCM, respectively (see Figure D-5). The goodness of fit test results showed that the general reservoir operation module developed could simulate the water release reasonably.

6.1.2.2 Flood reservoir operation rule

Flood rule is set up for the flood management that RID determined this rule after the flood crisis in 2011. This reservoir operation was actually operated in 2012. Regarding the flood operation, this study was adopted this rule to one of the reservoir operation, the objective for studying this rule is to investigate the flood operation affecting to the water management in term of water shortage and effectiveness for flood reduction. The results will use to optimize the suitable release rule. However, the limitation of this rule is the constant release – storage ratio; that will not vary with the storage in the water season. The release characteristic of this rule, it will be used to release the water in the end of dry season and mid-rainy season especially in March – April and July – August, respectively; and the amount of water release is about 29 – 35% and 34 – 40% of the storage. Hence, this reservoir will preserve the storage volume of reservoir to respond to the storm in the rainy season.

6.1.3 Water demand decision making module

The water demand decision-making module is a module for determining the crop cultivation area in downstream irrigation projects. The concept of the water demand system was based on the decision tree classification method. The logic of this system will decide the suitable cultivated area according to the probability of the effective storage at the end of the previous season, which means that the dam operation will determine the release rules from the residual water budget of the dam. This system was designed into 2 layers of decisions, including: 1) identifying the water season during the present period and 2) identifying the monthly level in the water season. The water demand rate (MCM/month/1000 rai) was calculated as the default values. Thus, it was calculated under a climate condition that included present, near future and far future period. The cropping pattern in this study was assumed as the present period, when farmers begin to cultivate in the wet season in the early May to the middle of November, and the dry season from mid-January to mid-April. According to the water demand decision-making module is the tool to determine the crop cultivation area based on the storage at the end of the previous season. The crop cultivation area and water demand will be affected by the change of storage which is operated by the reservoir operation rule. The crop cultivation area of Phitsanulok Irrigation Project was determined from the storages of Sirikit Dam, while the Chao Phraya Irrigation Project was determined from the storage of Sirikit and Bhumibol Dam (see the details in Appendix D.1.6).

6.1.4 Water network balance module

The water network balance of the Nan River Basin is considered on the lateral flow of Nan Sub-River Basin and the extraction points along Nan River. The main large irrigation projects which focused for evaluating the impact of reservoir operation including Phitsanulok and Chao Phraya Irrigation Projects. Their irrigation area is about 666,400 rais and 7,542,822 rais, respectively. Their irrigation water demand is about 710 MCM/year and 9,878 MCM/year, respectively. The water supply usage can be represented in the water extraction points in the water network flowchart shown as Figure F.1. The water supply usage was grouped by the location of districts and waterworks office, it included seven PWA and one MWA extraction points. However, the other water extraction points are the medium-, small- and pumping irrigation projects which were grouped by the location of districts include five irrigation extraction points.

The water network balance of The Lower Chao Phraya River Basin is necessary to consider the water budget which supplies to the main water user such as the lateral flow from Sakaekang and Upper Chao Phraya River Basin. Furthermore the minimum flow which release though Chao Phraya Diversion Dam such as the salinity flushing with flow rate 80 cms or 2,488 MCM/year, the waterworks which extracted from Chao Phraya River by PWA and MWA about 1,615 MCM/year. However the water supply record classifies the type of water user onto the domestic usage, the business usage and the industrial usage shown as Table 6.1 The total water supply usage of Nan River Basin can be separated into domestic 10.09 MCM/year, commercial 4.66 MCM/year and industrial 1.36 MCM/year, respectively. The total water supply usage of Chao Phraya River Basin can be separated into domestic 728 MCM/year, commercial 63 MCM/year and industrial 808 MCM/year, respectively. The constraint of water balance model at the Lower Chao Phraya River Basin is to supply for the salinity pushing, PWA and MWA as the first priority. These water usages will not occur the shortage event. On the other hand, the water balance module will allow the water deficit occur only in the irrigation projects.

Table 6.1 The summary of existing raw water demand for waterworks

River	Type	Raw water demand (MCM/year)							
		2005	2006	2007	2008	2009	2010	2011	2012
Nan	Domestic	11.49	12.09	11.16	8.19	8.19	8.54	8.77	10.09
	Commercial	5.23	5.49	5.07	3.75	3.75	3.90	4.00	4.66
	Industrial	1.61	1.70	1.56	1.13	1.13	1.18	1.21	1.36
Total		18.33	19.28	17.80	13.07	13.07	13.61	13.98	16.11
Chao Phraya	Domestic	46.57	52.11	65.41	71.43	71.43	70.97	74.85	85.64
	Commercial	31.57	35.58	47.55	52.68	52.68	52.40	55.38	63.10
	Industrial	39.74	45.25	60.96	68.79	68.79	68.03	72.00	82.69
Total		117.88	132.94	173.92	192.91	192.91	191.40	202.23	231.43
MWA	Domestic	532.2	540.1	571	586	615	629.7	625.2	642.32
	Commercial +Industrial	598.8	632.9	653	664.6	635.3	652.2	677.1	725.29
Total		1131	1173	1224	1250.6	1250.3	1281.9	1302.3	1367.6

In the water balance analysis, It has to set up the minimum flow though Chao Phraya Diversion Dam, and then the residual water will be the water supply for the Great Chao Phraya Irrigation Project. This water supply will be taken to multiply with the water allocation ratio for Chao Phraya Irrigation Project shown as Table F.7. Hence, this water allocation ratio was calculated from the portion between water allocation and water supply from the past pattern. This water allocation was summarized from the amount of release water through the east and west Chao Phraya Irrigation Project. The accuracy of water network balance model can be validated with the actual water release shown as Figure F.3 and F.5, respectively.

In the water network balance module, the release results would be used as the input variable of the water network balance module. The water balance model was validated by comparing the runoff at the control points with the observed runoff at the index runoff stations (see Figure F.1). The water balance model was calibrated and verified between 1979 to 2006 and 2007 to 2011 (See detail in Appendix F.2). The goodness of fit test of the model calibration and verification are shown in Table F.6 and F.7. In the model calibration, the results give the correlation (R^2) in range of 0.79 – 0.96, the root mean square error (RMSE) is in the range of 116.71 – 505.19 MCM/month, and the standard error (SE) is in the range of 113.87 – 492.60 MCM/month. On the other hand, in the model verification, the results give the correlation (R^2) in the range of 0.71 – 0.95, the root mean square error (RMSE) in the range of 82.24 – 254.35 MCM/month, and the standard error (SE) in the range of 169.15 – 521.60 MCM/month. The results show that the water network balance model developed can simulate the runoff along the main Nan River Basin reasonably.

The water network balance analysis would provide the results for evaluating the reservoir operation performance including the water deficit, water deficit per demand, seasonal stream flow and accumulative stream flow. The definition of these results as follows.

The water deficit was analyzed in the term of average values; it will be accounted the entire of monthly deficit with the zero values. The extreme water deficit was analyzed by accounting the monthly water deficit which has the water deficit per demand over 20%, and it will not include the zero values. The extreme analysis demonstrates the effectiveness of the module that how to reduce the severity of water shortage. It is represented the actually water deficit especially the lower storage and higher water demand in irrigation area, it has the chance to occur the severe deficit.

The seasonal stream flow analysis is calculated by using the accumulative stream flow in wet and dry season, it informed how much water supply at the control points that can be extracted for the agriculture usage especially for the small and pumping irrigation projects. If the greater amount of stream flow occur in the control points, it will give the high volume of water extraction. On the other hand, less amount of stream flow occur, it will give the high chance of water shortage.

The accumulative stream flow analysis is accounted from the stream flow volume in September to October. In the history of the Nan River Basin, most of flood events occur in these three months. The water network balance analysis, which based on the monthly basis, it cannot simulate exact flood volume at downstream. So the accumulative stream flow is the representative of the flooded events. However the baseline or capacity of the runoff station which occur the flood situation was considered from the historical flood volume and determine it as the capacity for the flood resistance. If the accumulative stream flow is over than this value, the event in the year will be identified or accounted as the flooded event.

6.1.5 Future water demand

The future water demand in this study was separated into 2 groups: the irrigation and waterworks groups. The main irrigated area was focused on the Phitsanulok and Chao Phraya Irrigation Project. The waterworks will be classified into 3 types: domestic, business and industrial type. The irrigated water demand in the future was considered from the cultivated area according to wet and dry season. The cultivated area will define the crop cultivation area and determined from the historical records. This study would not consider the new irrigation projects and the second round of second rice cropping. This study used the GCM climate data to calculate the irrigation water demand, which means that the future irrigation demand will depend on the GCM climate data and the irrigation area which varied with the storage of the reservoir. Regarding the waterworks, it was reviewed the predicted raw water demand based on the extension of PWA and MWA demand projection study shown in Table 6.2, respectively.

Table 6.2 The summary of future raw water demand for waterworks

a) Near Future

River	Type	Raw water demand (MCM/year)						
		2012	2015	2019	2024	2029	2034	2039
Nan	Domestic	8.33	8.69	9.46	10.28	11.51	12.26	13.16
	Business	3.80	3.97	4.33	4.72	5.29	5.65	6.07
	Industrial	1.14	1.18	1.27	1.36	1.51	1.59	1.70
Total		13.26	13.83	15.05	16.37	18.31	19.49	20.92
Chao Phraya	Domestic	78.53	86.72	106.82	126.95	151.86	171.16	192.31
	Business	58.42	64.74	80.22	95.70	114.78	129.67	145.94
	Industrial	76.76	85.23	105.95	126.64	152.11	172.05	193.80
Total		213.71	236.69	292.99	349.29	418.76	472.88	532.04
MWA	Domestic	642.32	670.37	740.49	810.61	880.73	950.85	1021
	Business+Industrial	725.29	769.83	881.18	992.52	1103.9	1215.2	1326.6
Total		1367.6	1440.2	1621.7	1803.1	1984.6	2166.1	2347.5

b) Far Future

River	Type	Raw water demand (MCM/year)						
		2012	2075	2079	2084	2089	2094	2099
Nan	Domestic	8.33	19.67	20.39	21.30	22.20	23.10	24.01
	Business	3.80	9.12	9.46	9.88	10.31	10.73	11.15
	Industrial	1.14	2.45	2.54	2.64	2.75	2.85	2.96
Total		13.26	31.24	32.39	33.82	35.25	36.69	38.12
Chao Phraya	Domestic	78.53	344.56	361.47	382.62	403.77	424.91	446.06
	Business	58.42	263.04	276.05	292.31	308.58	324.84	341.11
	Industrial	76.76	350.41	367.81	389.56	411.31	433.06	454.81
Total		213.71	958.01	1005.33	1064.50	1123.6	1182.82	1241.98
MWA	Domestic	642.32	1525.8	1581.9	1652	1722.2	1792.3	1862.4
	Business+Industrial	725.29	2128.2	2217.3	2328.7	2440	2551.4	2662.7
Total		1367.6	3654.1	3799.2	3980.7	4162.2	4343.6	4525.1

6.2 Impact assessment on general reservoir operation

For the impact assessment on general reservoir operations, the general reservoir operation rule was used to assess the effect of the climate change.

6.2.1 Irrigation water demand

The water demand rate which was adopted from Table 5.16 and area was calculated from the water demand decision making module, the irrigation water demand was shown in Table 6.3 The impact on water demand of the Phitsanulok Irrigation Project was assessed by comparing the future water demand with the present period. In the near future, the water demand in the wet season will decrease by -3.03% and less water demand will occur in July with a decrease of -16.34%. The water demand in the dry season will increase by 16.98% and more water demand will occur in March by 23.47% (as shown in Figure 6.2a). In the far future, the water demand in the wet season will decrease by -3.52%; however, less water demand will occur in August with a decrease of -16.49%, while the water demand in the dry season will tend to increase by 21.17%, especially in March by 33.08% (as shown in Figure 6.2a).

In both of the near and far future, the crop cultivation area and water demand rate in the wet season will not change significantly and that will cause no change in water demand. On the other hand, the crop cultivation area and water demand rate in dry season will tend to increase that will bring about higher water demand compared with the present period.

The impact on water demand of the Chao Phraya Irrigation Project also can be assessed by comparing the future water demand with the present period. In the near future, the water demand will increase 11.13% in the wet season and more water demand will occur in May with an increase of 37.22%. The water demand in the dry season will increase 16.32% and more water demand will occur in March by 37.09% (as shown in Figure 6.2b). In the far future, the water demand in the wet season will decrease by -2.89% and less water demand will occur in August with a decrease of -15.65%. The water demand in the dry season will increase by 21.38% and more water demand will occur in March by 38.16% (as shown in Figure 6.2b).

In the near future, the water demand in wet season tends to increase even though the crop cultivation area and water demand rate have no change. Because the crop cultivation area in dry season increase induce to the planting area need more water at the end of cultivated season (cultivated season begins from December to May) which affected to early of wet season, especially in May. On the other hand, the crop cultivation area and water demand rate in dry season will tend to increase that will bring about higher water demand compared with the present period.

In the far future, the crop cultivation area in wet season tend to increase but the water demand rate tend to decrease that will bring about lower water demand compared with the present period. On the other hand, the crop cultivation area and water demand rate in dry season will tend to increase that will bring about higher water demand compared with the present period.

Table 6.3 Crop cultivation area and water demand under general dam operation

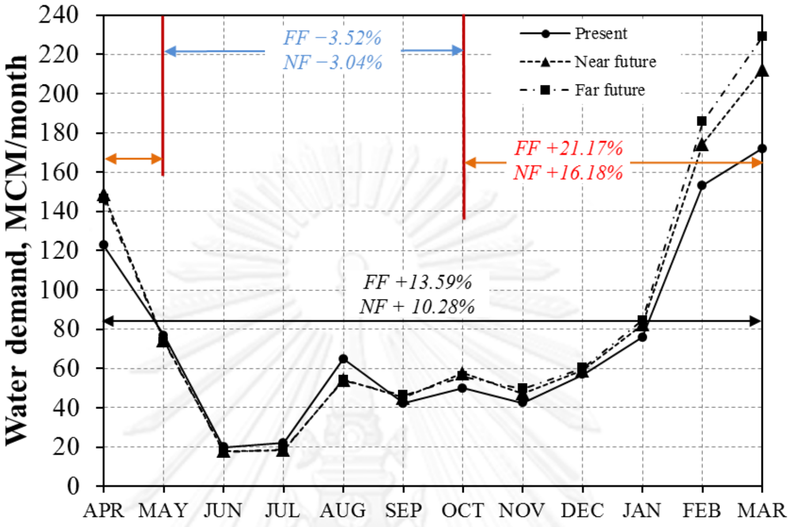
Project	Variable	Crop	Present			Near future			Far future		
			Wet	Dry	Annual	Wet	Dry	Annual	Wet	Dry	Annual
PSK	Crop cultivation area (x 1000 rais)	Paddy	630	624	1,254	621	638	1,259	618	643	1,260
		Upland Crop	29.48	31.09	60.57	29.48	31.09	60.57	29.48	31.09	60.57
	Water demand rate (MCM/1000 rais)	Paddy	0.93	1.63	2.56	0.86	1.74	2.6	0.85	1.81	2.67
		Upland Crop	0.65	1.24	1.88	0.6	1.33	1.94	0.61	1.41	2.02
	Water demand (MCM)		276	623	899	268	724	992	266	755	1,022
	Change (%)					-3.04	16.18	10.28	-3.52	21.17	13.59
CHY	Crop cultivation area (x 1000 rais)	Paddy	4,648	3,122	7,770	4,670	3,653	8,323	4,699	3,612	8,310
		Upland Crop	23.26	29.75	53.01	23.09	39.59	62.68	22.67	35.44	58.11
	Water demand rate (MCM/1000 rais)	Paddy	1.3	1.07	2.37	1.24	1.16	2.4	1.2	1.18	2.38
		Upland Crop	0.6	1.19	1.79	0.56	1.3	1.86	0.5	1.36	1.86
	Water demand (MCM)		5,681	4,428	10,109	6,313	5,151	11,463	5,518	5,375	10,893
	Change (%)					11.13	16.32	13.40	-2.86	21.38	7.76

Remark : PSK = Phitsanulok Irrigation Project, CHY = Chao Phraya Irrigation Project

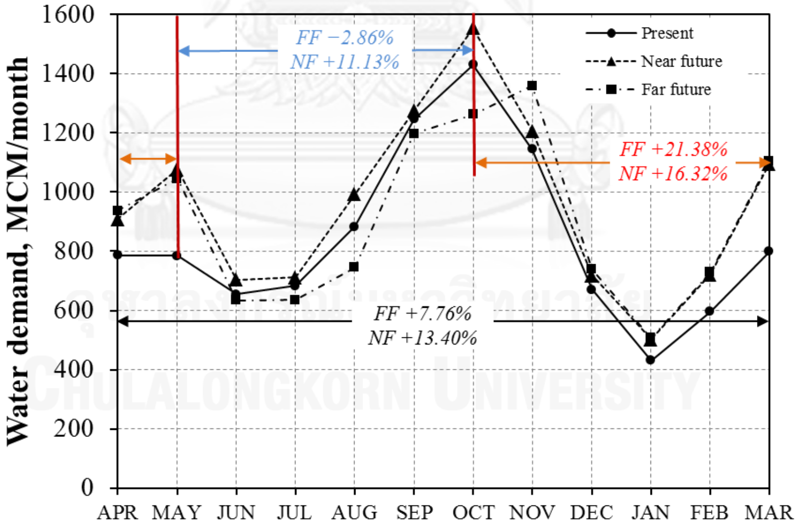
6.2.2 Reservoir water balance

In the near future, the monthly storage under general rule in the wet season will increase 7.66% to 8.54%, and especially an 8.54% increase in May, while the monthly storage in the dry season will increase 6.64% to 8.34%, especially with an 8.34% increase in April (shown in Figure 6.3). On the other hand, the monthly release in the wet season will increase 0.22% to 19.17%, especially with a 19.17% increase in September, while the monthly release in the dry season will vary in range from -1.80% to 18.16%, especially with an 18.16% increase in December (shown in Figure 6.3). In far future, the monthly storage in the wet season will increase 12.16% to 15.32%, especially with an increase of 15.32% in July, while the monthly storage in the dry season will increase 12.00% to 13.55% especially with a 13.55% increase in April (shown in Figure 6.3). On the other hand, the monthly release in the wet season will increase 1.73% to

44.05%, especially with a 44.05% increase in September, while the monthly release in the dry season will increase 0.84% to 17.39%, especially with an increase of 17.39% in December (shown in Figure 6.3).



(a) Phitsanulok Project



(b) Chao Phraya Project

Figure 6.2 Monthly mean water demand under general dam operation

In the case of general dam operations, in the near future, the slightly increasing inflows inducing the annual storage will increase 7.93%, while the annual release will not change significantly (+4.74%). In the far future, the increasing inflow inducing the annual storage will tend to increase by 12.70%, and the annual release will tend to increase by 9.53% (shown in Figure 6.4). The results imply that the storage in the near future will increase due to more release and high demand, while the storage in the far future can be expected to be higher due to the increasing inflow. However the release will increase according to higher inflow and storage in both the wet and dry season. Additionally, the probability of annual release reveals that the magnitude of the release will be higher, especially the mostly probability of release will increase as shown in Figure 6.4.

Table 6.4 Summary of the impacts on storage and release under general dam operation

Variable	Present			Near future			Far future		
	Wet	Dry	Annual	Wet	Dry	Annual	Wet	Dry	Annual
Inflow (MCM)	5,189	839	6,028	5,523	845	6,369	5,845	903	6,748
Change (%)	-	-	-	6.44	0.74	5.64	12.64	7.56	11.93
Storage (MCM)	5,026	7,724	6,375	5,445	8,316	6,881	5,707	8,664	7,185
Change (%)	-	-	-	8.34	7.66	7.93	13.55	12.16	12.70
Release (MCM)	2,389	3,299	5,688	2,531	3,569	5,958	2,714	3,663	6,230
Change (%)	-	-	-	5.98	8.18	4.74	13.62	11.01	9.53

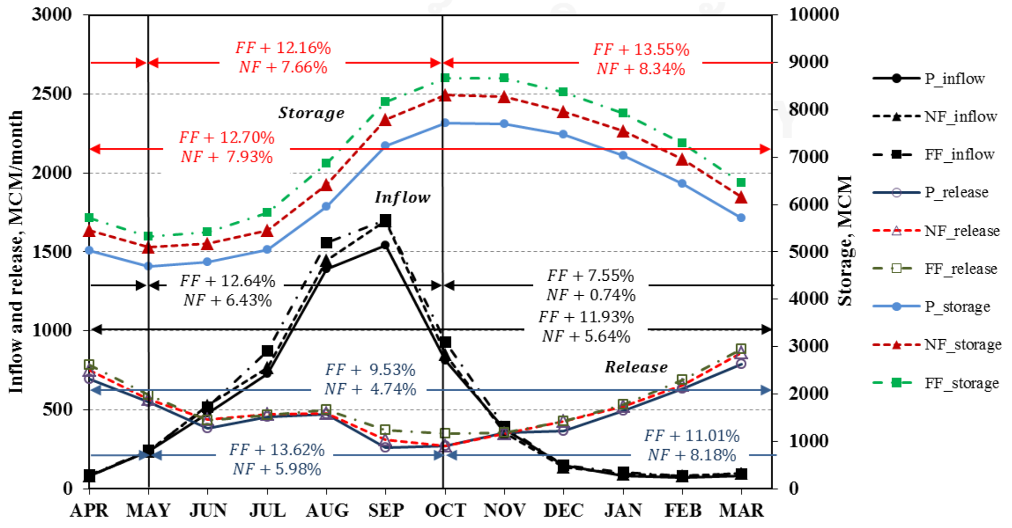


Figure 6.3 Comparison of inflow, storage and release under general dam operation

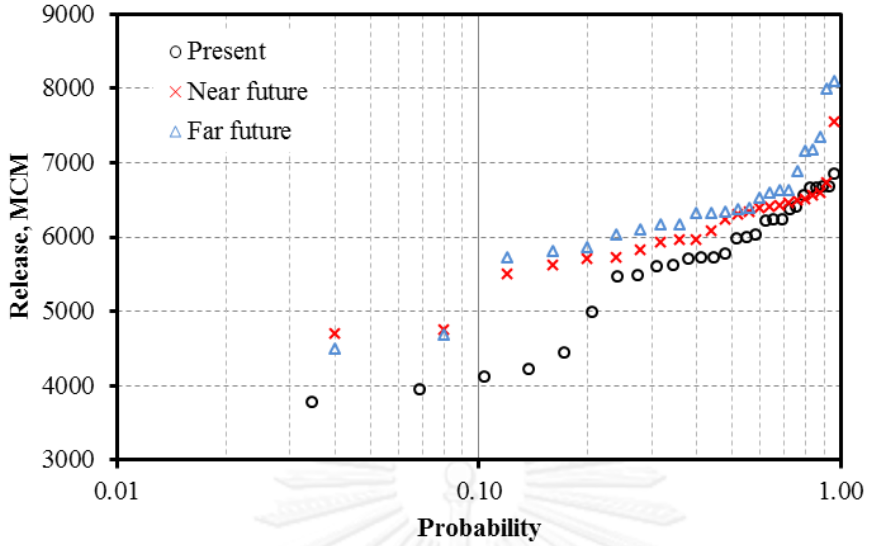


Figure 6.4 Probability of annual release under general dam operation

6.2.3 Spillage

The impact on water spillage was used to evaluate the water overflow through the spillway. From the monthly results it was found that concerning general dam operations in the near future, the average spillage will increase 2033% compared with present period and maximum spillage will not change significantly (3.18%). On the other hand, regarding general dam operations in the far future, the average spillage will increase 936% and maximum spillage will increase 18.47%. However the number of spillages in far future will be higher than in the near future due to the higher inflow. A summary of the average and maximum spillage is shown in Table 6.3.

Table 6.5 Summary of average and maximum spillage under general dam operation

Spillage	Actual	Present	Near future	Far future
Average (MCM)	393.4	19.8	422.3	205.1
Change (%)	-	-	2033	936
Maximum (MCM)	1164.8	409.3	422.3	484.9
Change (%)	-	-	3.18	18.47
Number of sillage (years)	7	3	3	7

6.2.4 Water shortage

The water shortage indices of the related irrigation project were assessed from the water deficit, water deficit per demand, number of water shortage, and frequency and maximum of water shortage length. The water deficit per demand is one of the indices that show the relative water deficit per demand of the crop cultivation area. The water demand decision making module determines the crop cultivation area according to the storage at the end of the season. Consequently, the water deficit per demand will be used to evaluate the water shortage under dam operations.

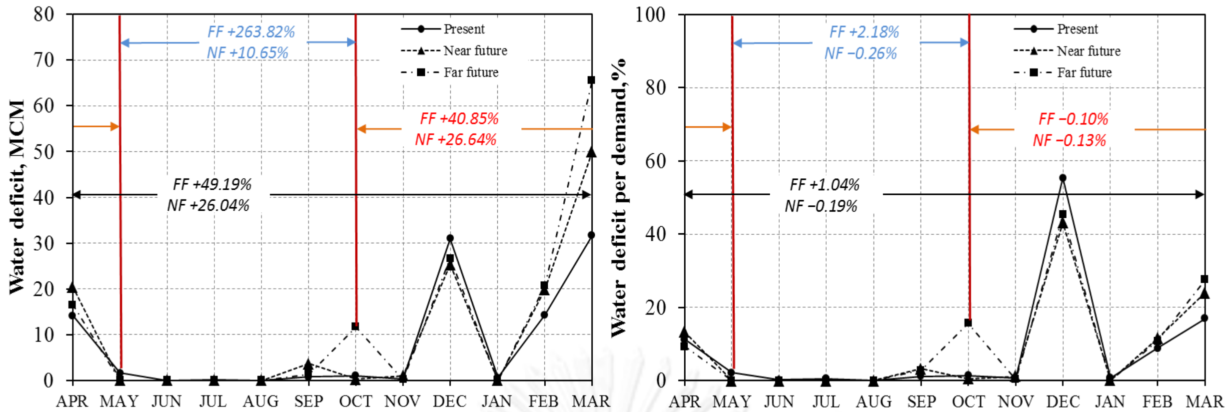
The impact on water deficit per demand of the Phitsanulok Irrigation Project (PSK) was assessed by comparing the future water deficit with the present period. In the near future, the water deficit per demand in the wet season will decrease -0.26%; however, more water deficit per demand will occur in September with an increase of 2.11%. The water deficit per demand in the dry season will decrease not significantly (-0.13%); however, more water deficit will occur in March by 6.97% (shown in Figure 6.5a). In the far future, the water deficit per demand in the wet season will increase by 2.18%; however, the greater water deficit per demand will occur in October with an increase by of 14.23%. On the other hand, the water deficit in the dry season will not change significantly (-0.10%), however, more water deficit will occur in March by 10.61%. (as shown in Figure 6.5b).

For the water deficit per demand of Chao Phraya Irrigation Project (CHY); in the near future, the water deficit in wet season, water deficit will increase not significantly (+0.21%); and, greater water deficit per demand will occur in May with an increase of 3.14%. The water deficit per demand in the dry season will increase by 6.84%; and a greater water deficit per demand will occur in February by 10.67% (as shown in Figure 6.5c). In the far future, the water deficit per demand in the wet season will decrease not significantly (-0.98%), while the water deficit per demand in the dry season will increase by 4.32%, and a greater water deficit per demand will occur in January by 15.24%, respectively (shown in Figure 6.5d).

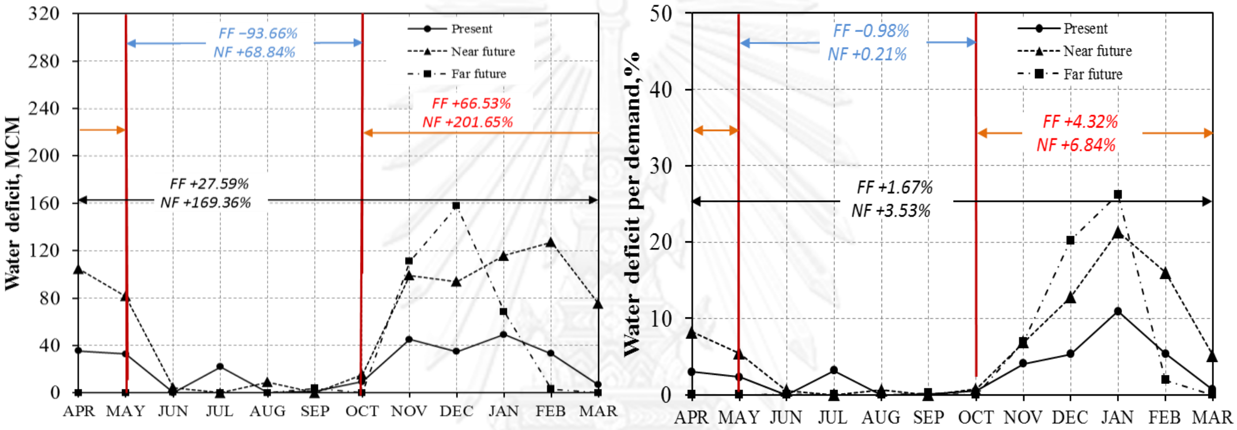
In the near future, the water deficit per demand in Phitsanulok Irrigation Project will tend to decrease due to the higher release in both the wet and dry seasons. However, Chao Phraya Irrigation Project, the water deficit tends to increase due to higher water demand especially water supply for domestic and industrial tend to increase. On the other hand, in the far future, the water deficit per demand of the Phitsanulok Irrigation Project will tend to increase in dry season due to higher water demand. Even if Sirikit Dam releases more water it will be still insufficient to supply this irrigation project. Furthermore, the water deficit per demand of the Chao Phraya Irrigation Project in dry season will tend to increase due to higher water demand downstream.

Table 6.6 Summary of water shortage by general dam operation

Irrigation Project	Statistics	Actual (28 years)			Present (28 years)			Near future (25 years)			Far future (25 years)		
		Wet	Dry	Annual	Wet	Dry	Annual	Wet	Dry	Annual	Wet	Dry	Annual
Phitsanulok	Mean (MCM)	17	44	60	4	92	96	4	117	121	13	130	143
	Maximum (MCM)	195	214	314	86	311	397	89	307	396	85	238	240
	Average percentage of water deficit per water demand (%)	6.07	11.67	8.87	0.88	15.62	8.25	0.62	15.50	8.06	3.06	15.52	9.29
	Maximum percentage of water deficit per water demand (%)	55.54	44.46	42.39	11.79	41.21	20.81	10.00	32.26	16.13	21	23	18
	Number of water shortage (years)	15	26	27	4	27	27	4	23	23	6	23	23
	Frequency (times/season,times/year)	0.36	0.35	0.27	0.25	0.44	0.24	0.17	0.51	0.27	0.19	0.50	0.28
	Maximum of continuous water shortage year (years)	-	-	20	-	-	27	-	-	24	-	-	24
Chao Phraya	Mean (MCM)	238	266	505	66	204	270	207	652	859	155	340	495
	Maximum (MCM)	1712	1587	2,426	571	1730	2,301	1052	2624	3,676	2017	1346	2,221
	Average percentage of water deficit per water demand (%)	3.53	4.79	4.16	1.02	4.91	2.97	1.24	11.75	6.49	0.05	9.23	4.64
	Maximum percentage of water deficit per water demand (%)	29.80	62.31	31.08	8.70	30.60	18.90	11.53	44.64	22.32	11.05	33.05	16.52
	Number of water shortage (years)	12	18	20	7	14	15	9	21	21	5	20	20
	Frequency (times/season,times/year)	0.28	0.32	0.23	0.21	0.38	0.23	0.19	0.43	0.25	0.17	0.22	0.13
	Maximum of continuous water shortage year (years)	-	-	9	-	-	4	-	-	22	-	-	13



(a) Water deficit of Phitsanulok (b) Water deficit per demand of Phitsanulok



(c) Water deficit of Chao Phraya (d) Water deficit per demand of Chao Phraya

Remark : The % relative change of water deficit in NF = (Water deficit in NF - Water deficit in PR) / Water deficit in PR x 100, The % relative change of water deficit in FF = (Water deficit in FF - Water deficit in PR) / Water deficit in PR x 100,

The % relative change of water deficit per demand in NF = water deficit per demand in NF - water deficit per demand in PR, The % relative change of water deficit per demand in FF = water deficit per demand in FF - water deficit per demand in PR

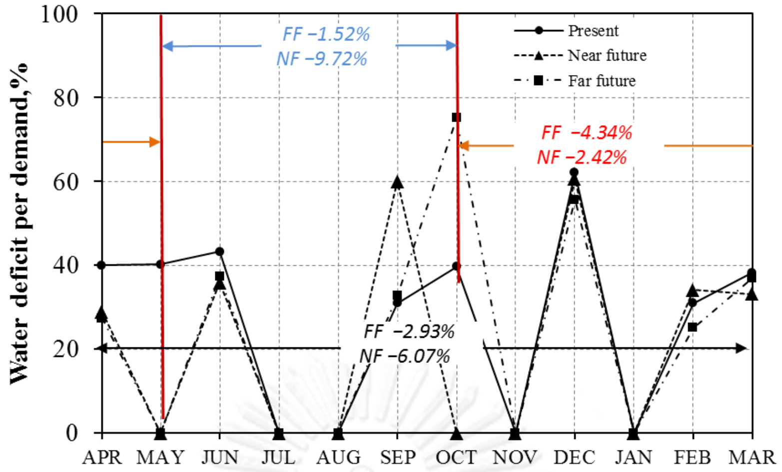
Figure 6.5 Monthly mean water deficit and water deficit per demand of Phisanulok and Chao Phraya Irrigation Project under general dam operation

However, the water shortage, which was evaluated according to the mean values, could not reveal the extreme shortage events exactly that may occur in the future. This study examined the extreme shortage events by accounting the water deficit values over 20% compared with the water demand. For example, if the water deficit value of month was equal or over 20%, it was considered that the shortage event would occur in that month. The monthly mean water deficit and water deficit per demand for the extreme shortage events were calculated from that accounted value. The extreme shortage according to general dam operations is summarized in Table 6.7. From the results, it was found that the mean water deficit of Phitsanulok Irrigation Project in wet season will decrease in the near and far future, while the water deficit in dry season will increase in the near and far future. Because the rainfall in the Lower Nan River Basin tend to increase in wet season that cause the water demand rate decrease, while the rainfall tend to decrease in dry season that cause the water demand rate increase. On the other hand, the mean water deficit of Chao Phraya Irrigation Project in wet season tend to decrease in both near and far future, the water deficit in dry season tend to increase in both near and far future. Because the rainfall in the Lower Chao Phraya River Basin tend to increase in wet season that cause the water demand rate decrease, while the rainfall tend to decrease in dry season that cause the water demand rate increase.

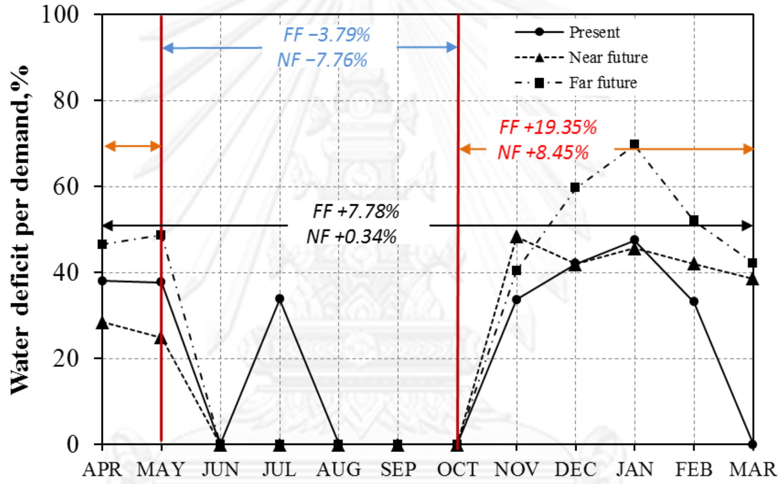
From Figure 6.6(a), it was found that there were some peaks of water deficit per demand occur in June, September, October, December and March, due to the less rainfall which occur in the drought year cause the higher water demand in these months.

Table 6.7 Summary of the extreme shortage by general dam operation

Project	Statistics	Actual (28 years)			Present (28 years)			Near future (25 years)			Far future (25 years)		
		Wet	Dry	Annual	Wet	Dry	Annual	Wet	Dry	Annual	Wet	Dry	Annual
Phitsanulok	Mean (MCM)	218	200	418	92	204	296	89	216	304	80	221	300
	Average percentage of water deficit per water demand (%)	51.5	39.6	45.6	25.7	28.6	27.13	16	26.13	21.06	24.18	24.21	24.19
	Number of water shortage (years)	9	21	25	2	11	23	1	16	20	2	16	20
Chao Phraya	Mean (MCM)	1239	2200	3440	800	1519	2319	353	2570	2924	1058	3310	4368
	Average percentage of water deficit per water demand (%)	23.63	44.92	34.28	11.91	32.42	22.17	4.15	40.87	22.51	8.13	51.77	29.95
	Number of water shortage (years)	6	8	10	0	4	4	0	12	14	0	16	19



(a) Phitsanulok Project



(b) Chao Phraya Project

Remark : The % relative change of water deficit per demand in NF = water deficit per demand in NF - water deficit per demand in PR, The % relative change of water deficit per demand in FF = water deficit per demand in FF - water deficit per demand in PR

Figure 6.6 Water deficit per demand of Phitsanulok and Chao Phraya Irrigation Project under general dam operation in extreme shortage case

6.2.5 Stream flow at the control points

In the near future, the seasonal stream flow in the wet season will increase by 5.48% to 9.68% compared with the present period, while the seasonal stream flow in the dry season will not change significantly (0.78% to 3.22%). In the far future, the seasonal stream flow in the wet season will increase by 12.74% to 19.55% in relation to the present period while the seasonal stream flow in the dry season will increase by 9.42% to 14.21% in relation to the present period.

In the near future, the annual stream flow at the control points will increase 4.20% to 6.83% compared with present period, while the annual stream flow in the far future will increase 11.24% to 15.94%. The higher rainfall in far future will cause a higher stream flow in the Upper and Lower Nan River Basin and a higher release from Sirikit Dam. A summary of seasonal and annual stream flows at the control points are shown in Table 6.8.

Table 6.8 Summary of seasonal and annual stream flow at the control points

Control point	Present			Near future			Far future		
	Wet (MCM)	Dry (MCM)	Annual (MCM)	Wet (MCM)	Dry (MCM)	Annual (MCM)	Wet (MCM)	Dry (MCM)	Annual (MCM)
N.12A	2869	3607	6475	3041	3723	6764	3283	3946	7229
Change (%)	-	-	-	6.00	3.22	4.45	14.43	9.42	11.64
N.60	3938	4164	8102	4153	4288	8442	4439	4574	9013
Change (%)	-	-	-	5.48	2.98	4.20	12.74	9.83	11.24
N.27A	3075	2651	5725	3327	2696	6023	3676	2920	6596
Change (%)	-	-	-	8.20	1.71	5.19	19.55	10.18	15.21
N.5A	4729	3067	7797	5069	3100	8169	5494	3380	8875
Change (%)	-	-	-	7.18	1.07	4.78	16.17	10.21	13.82
N.7A	6754	3881	10635	7257	3911	11167	7672	4275	11948
Change (%)	-	-	-	7.43	0.78	5.00	13.59	10.17	12.34
N.67	9520	4859	14379	10441	4919	15361	11027	5361	16388
Change (%)	-	-	-	9.68	1.24	6.83	15.83	10.33	13.97
C.2	13984	8965	22949	15274	9195	24470	16368	10239	26607
Change (%)	-	-	-	9.23	2.57	6.63	17.04	14.21	15.94

Regarding the flood impact assessment, the maximum accumulative runoff from August to October was used to evaluate the effect from the dam operation along the main Nan River. The maximum capacity was set as the maximum limitation (see Table 6.9), which started to cause the flood event. Hence, this value was set up from the historical flood in each runoff station. It was found that the maximum accumulative runoff of observed data was higher than the present GCM data due to the present GCM rainfall provides the lower amount of runoff compared with the observed runoff.

In the near future, the mostly runoff stations revealed that the maximum accumulative runoff will decrease 0.4% to 17.07% compared with the present period due to the lower water extraction along the main Nan River Basin; however, N.12A and N.67 will tend to increase by 17.58% and 2.2% because the N.12A will receive a higher lateral flow from the Nam Pad Sub River Basin and N.67 will receive a higher lateral flow from the Yom River Basin and Lower Nan River Basin. The higher change in the runoff will occur at N.12A (17.58%).

In the far future, it was revealed that for most of the runoff stations, the maximum accumulative runoff will increase 12.7% to 65.55% compared with the present period, except that C.2 will tend to decrease by 5.58% compared with the present period. From the results it can be implied that the flood event under general dam operations in the near future will decrease in terms of magnitude and frequency. On the other hand, the general dam operations will release higher in the far future because the higher inflow and lateral flow will affect the flood problem in terms of magnitude and frequency. Additionally, the probability of maximum accumulative runoff at the C.2 runoff station reveals that the magnitude of runoff will be higher, especially the mostly probability of runoff will be increase. A summary of the maximum accumulative runoff under general dam operations is shown in Table 6.9.

Table 6.9 Summary of maximum accumulative runoff under general dam operation

Control point	Maximum capacity (MCM)	Maximum accumulative runoff (MCM)				Number of flood event (year)			
		Obs	P	NF	FF	Obs	P	NF	FF
N.12A	2756	4491	2264	2662	3748	2	0	0	2
N.60	3825	5549	3572	3300	5341	2	0	0	2
N.27	2916	5701	3291	3278	5190	5	3	1	4
N.5A	4804	8230	5617	5141	7420	4	2	1	2
N.7A	6147	10793	7798	6467	10598	7	6	1	5
N.67	7801	12904	12649	12927	14256	10	9	7	9
C.2	12087	26485	21440	21326	20243	7	4	6	10

From Figure 6.8, It was found that the reservoir operation in the near and far future will affect to the higher baseflow but the high flow will not much change.

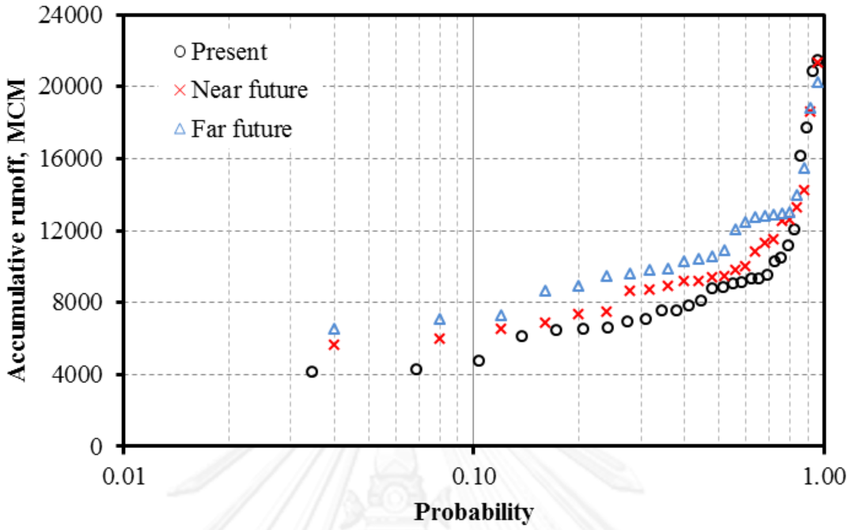


Figure 6.7 Probability of accumulative monthly runoff at C.2 under general dam operation

6.3 Impact assessment on flood dam operation

Due the flood event in 2011, Thailand's government planned to solve the flooding problem using structured and non-structured measures such as the infrastructure construction and efficiency improvement of the water management system. Modification of dam operations was one of the important short-term measures that the government used to control the flood water. The government has modified the main dam operation rule curves to respond to a flood event that may occur in future (RID, 2012). The flood reservoir operation model was developed based on the revised reservoir operation rule curve and operation plan for 2012. The basic concept of this modification was to decrease the water storage in the dam during the late rainy season to ease the flood pressure by releasing more water in the dry season and early rainy season. For the above reason, this study took the flood dam operation rule involve to be one of the alternative release rules, and the proportion of water release and effective storage for 2012 was used as the flood water operation pattern. The release–storage ratio for flood dam operations is shown in Table D.2.

6.3.1 Irrigation water demand

The Phitsanulok cultivation area must vary with the water demand decision-making criteria. The water demand of the Phitsanulok Irrigation Project was used to assess the changes by comparing the future water demand with the present water demand. In the near future, the water demand in the wet season will not change significantly; however, less water demand will occur in July with a decrease of -15%. The water demand in the dry season will increase by 14.88% and the water demand will increase in March by 21.20% (as shown in Figure 6-8a).

In the far future, the water demand in the wet season will not change significantly; however, less water demand will occur in August with a decrease of 13.64%. On the other hand, the water demand in the dry season will tend to increase by 19.45%, especially in March, by 30.24% (as shown in Figure 6-8a).

In the near and far future period, the crop cultivation area the wet season will not change significantly but water demand rate tend to decrease that will cause lower water demand. On the other hand, the crop cultivation area in dry season will not change significantly, the water demand rate will tend to increase, and this will cause the water demand to increase.

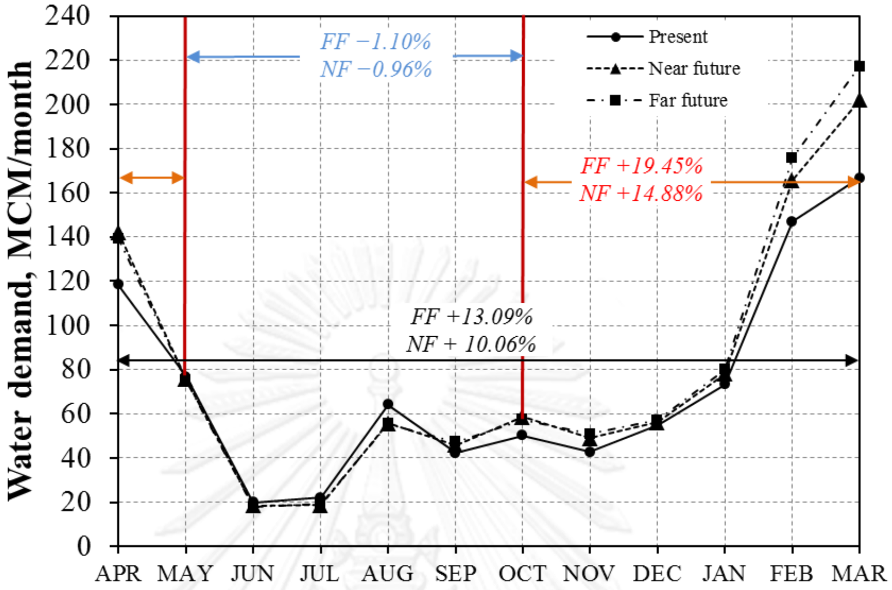
The Chao Phraya cultivation area varied with the water demand decision-making criteria. For the water demand of the Chao Phraya Irrigation Project, in the near future, the water demand will increase 22.56% in the wet season and more water demand will occur in May with a increase of 32.84%. The water demand in the dry season will increase by 25.48% and more water demand will occur in March by 43.37% (as shown in Figure 6-8b). In the far future, the water demand in the wet season will increase 3.33% and more water demand will occur in September with an increase of 9.16%, while the water demand in the dry season will increase 15.47% and more water demand will occur in November by 33.89% (as shown in Figure 6-8b).

In the near and far future, the water demand in wet season tends to increase even though the crop cultivation area and water demand rate have no change. Because the crop cultivation area in dry season increase induce to the planting area need more water at the end of cultivated season (cultivated season begins from December to May) which affected to early of wet season, especially in May. On the other hand, the crop cultivation area and water demand rate in dry season will tend to increase that will bring about higher water demand compared with the present period. From the results it can be implied that the crop cultivation is the greater influencing factor on the water demand.

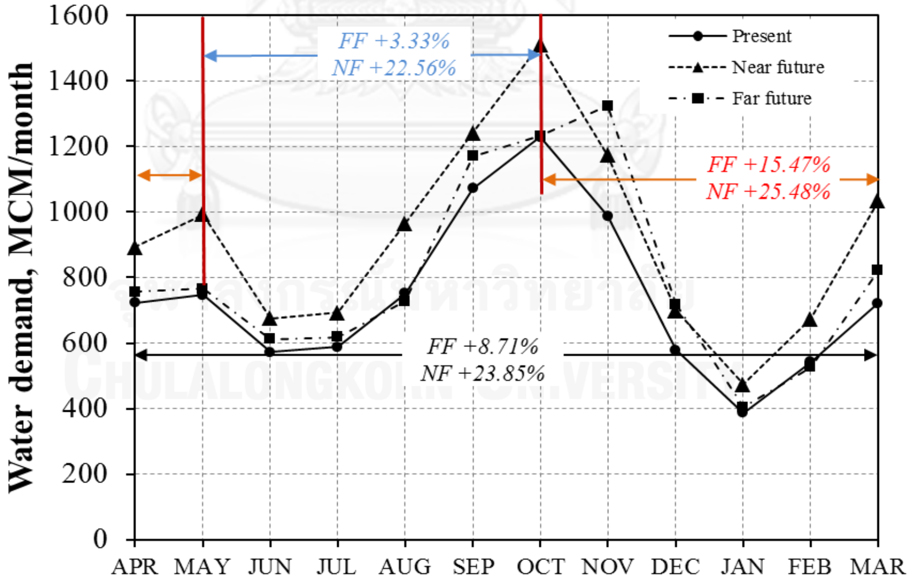
Table 6.10 Crop cultivation area and water demand under flood dam operation

Project	Variable	Crop	Present			Near future			Far future		
			Wet	Dry	Annual	Wet	Dry	Annual	Wet	Dry	Annual
PSK	Crop cultivation area (x 1000 rais)	Paddy	631	600	1,230	636	606	1,242	635	608	1,243
		Upland Crop	29	31	61	29	31	61	29	31	61
	Water demand rate (MCM/1000 rais)	Paddy	0.93	1.63	2.56	0.86	1.74	2.6	0.85	1.81	2.67
		Upland Crop	0.65	1.24	1.88	0.6	1.33	1.94	0.61	1.41	2.02
	Water demand (MCM)		275	603	878	273	693	967	272	720	993
	Change (%)					-0.96	14.88	10.06	-1.10	19.45	13.09
CHY	Crop cultivation area (x 1000 rais)	Paddy	4,546	3,349	7,895	4,546	3,416	7,962	4,578	2,659	7,238
		Upland Crop	24	37	62	24	39	64	24	30	54
	Water demand rate (MCM/1000 rais)	Paddy	1.3	1.07	2.37	1.24	1.16	2.4	1.2	1.18	2.38
		Upland Crop	0.6	1.19	1.79	0.56	1.3	1.86	0.5	1.36	1.86
	Water demand (MCM)		4,958	3,940	8,899	6,077	4,944	11,021	5,123	4,550	9,673
	Change (%)					22.56	25.48	23.85	3.33	15.47	8.71

R55emark : PSK = Phitsanulok Irrigation Project, CHY = Chao Phraya Irrigation Project



(a) Phitsanulok Project



(b) Chao Phraya Project

Figure 6.8 Monthly mean water demand under flood control dam operation

6.3.2 Reservoir water balance

In the near future, the monthly storage in the wet season will not change significantly (+1.81% to +3.91%), while the monthly storage in the dry season also will not change significantly (+2.19% to +3.15%) (shown in Figure 6.9). On the other hand the monthly release in the wet season will increase 4.92% to 7.24%, especially in July at 7.24%, while the monthly release in the dry season will increase 5.33% to 7.33% especially with a 7.33% increase in April (shown in Figure 6.9)

In the far future, the monthly storage in the wet season will increase 2.97% to 7.07% especially with a 7.07% increase in October, while the monthly storage in dry season will increase from 3.62% to 6.52%, especially with a 6.52% increase in November (shown in Figure 6.9). On the other hand, the monthly release in the wet season will increase 9.82% to 14.67%, especially with a 14.67% increase in August, while the monthly release in the dry season will increase 11.35% to 12.38%, especially with a 12.38% increase in November (shown in Figure 6.9). In the case of flood dam operations, in the near future, the slight inflow will cause the annual storage to increase by 3.20%, while the annual release will increase by 4.51% compared with the present. In the far future, however, the increasing inflow will cause the annual storage to increase by 5.75%, and the annual release will tend to increase 10.14% (shown in Table 6.10). Additionally, the probability of annual release reveals that the magnitude of the release will be higher, especially the mostly probability of release will increase as shown in Figure 6.10.

Table 6.11 Summary of the impact on storage and release under flood dam operation

Variable	Present			Near future			Far future		
	Wet	Dry	Annual	Wet	Dry	Annual	Wet	Dry	Annual
Inflow (MCM)	5,189	839	6,028	5,523	845	6,369	5,845	903	6,748
Change (%)	-	-	-	6.44	0.74	5.64	12.64	7.56	11.93
Storage (MCM)	4,096	6,642	5,369	4,185	6,896	5,541	4,244	7,112	5,678
Change (%)	-	-	-	2.19	3.82	3.20	3.62	7.07	5.75
Release (MCM)	2,568	3,233	5,801	2,731	3,470	6,062	2,887	3,648	6,389
Change (%)	-	-	-	6.36	7.33	4.51	12.45	12.82	10.14

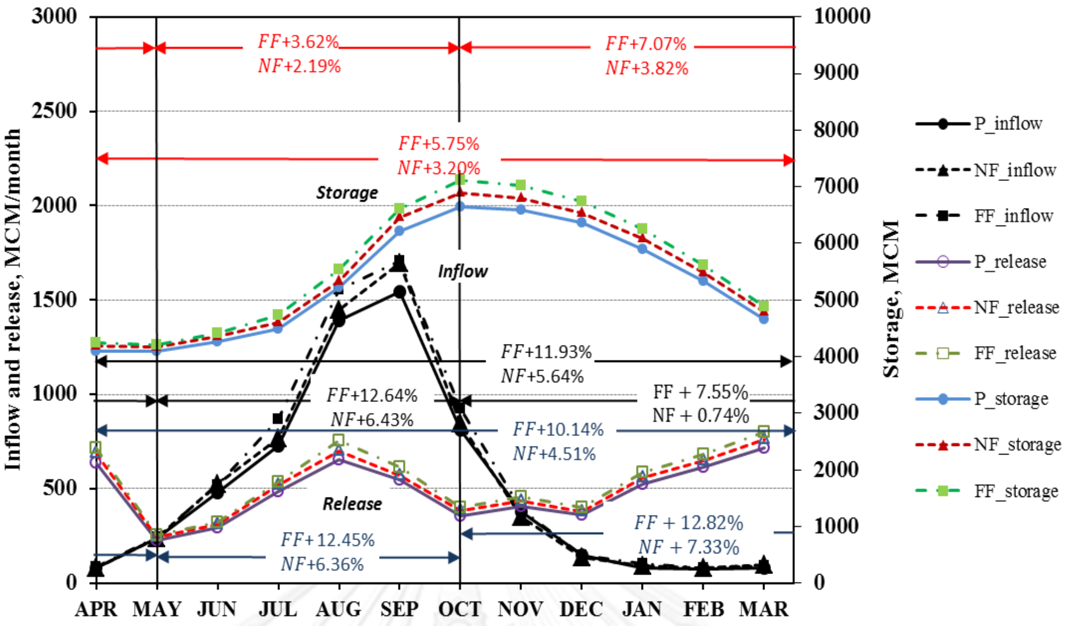


Figure 6.9 Comparison of inflow, storage and release under flood dam operation

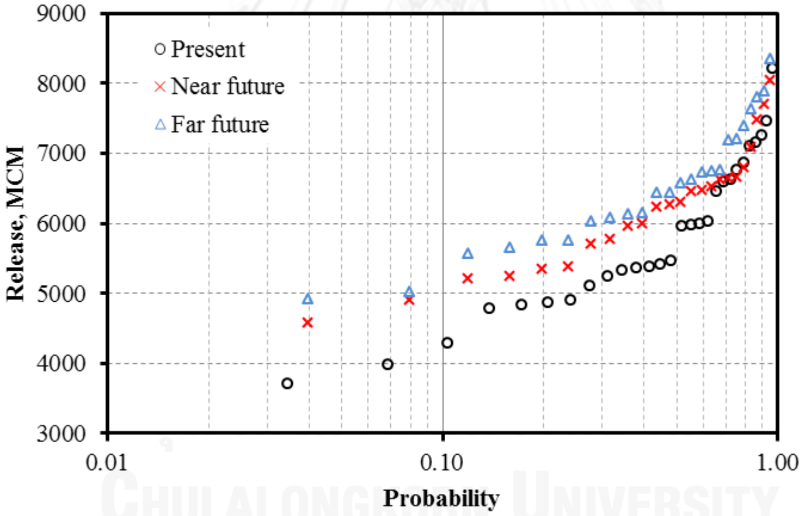


Figure 6.10 Probability of annual release under flood control dam operation

6.3.3 Spillage

From the result was found that flood dam operation in the near and far future; the average and maximum spillage will not occur. It is implied that the flood dam operation can reduce more effectively. The summary of average and maximum spillage shows as Table 6.12.

Table 6.12 Summary of average and maximum spillage under flood dam operation

Spillage	Actual	Present	Near future	Far future
Average (MCM)	393.4	114.2	-	-
Maximum (MCM)	1164.8	114.2	-	-
Change (%)	-	-	-	-
Number of sillage (years)	7	1	-	-

6.3.4 Water shortage

The change in the water shortage of Pitsanulok Irrigation Project was assessed by comparing the future water deficit per demand with the present water deficit per demand. In the near future, the water deficit per demand in the wet season will tend to decrease by -2.42%; and a less water deficit per demand will occur in October by 2.33%. On the other hand, the water deficit per demand in the dry season will decrease not significantly (-0.29%), but a greater water deficit per demand will occur in December by 60.77% (as shown in Figure 6-11a). In the far future, the water deficit per demand in the wet season will tend to decrease by -1.54; and a less water deficit per demand will occur in May with an decrease of -4.02%, while the water deficit per demand in the dry season will tend to decrease by -2.27%, especially in February, with an decrease of -8.38% (as shown in Figure 6-11b).

For the water shortage of the Pitsanulok Irrigation Project, in both near and far future, the water deficit will tend to decrease in both wet and dry season due to the crop cultivation area will not quite much change compared with the present period and the Sirikit Dam release more water to Phitsanulok Irrigation Project according to the flood release rule that releases more water in both wet and dry season..

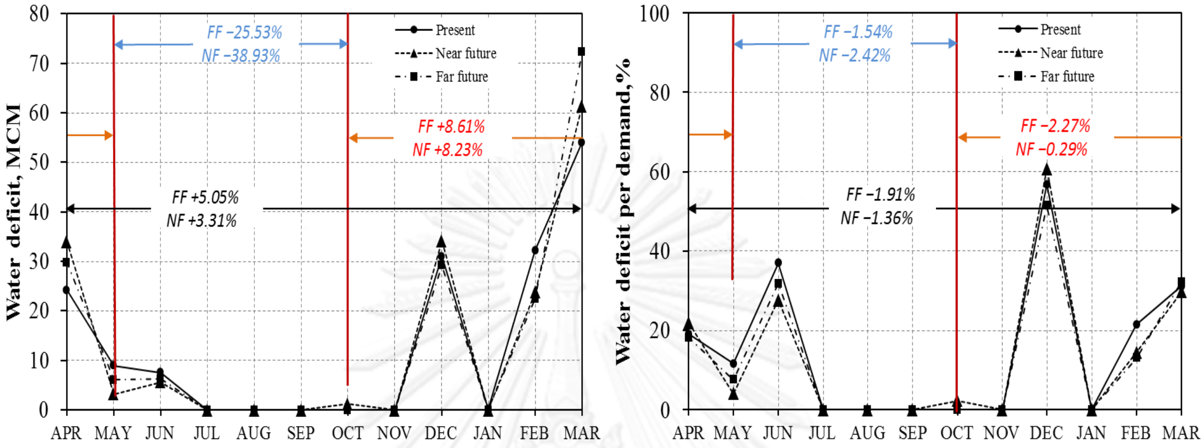
For the water shortage of the Chao Phraya Irrigation Project, in both near and far future, a water deficit per demand will tend to increase in both wet and dry season especially in December, due to the crop cultivation area and the water supply for domestic and industrial downstream will tend to increase (as shown in Figure 6-11d).

Table 6.13 Summary of water deficit by flood dam operation

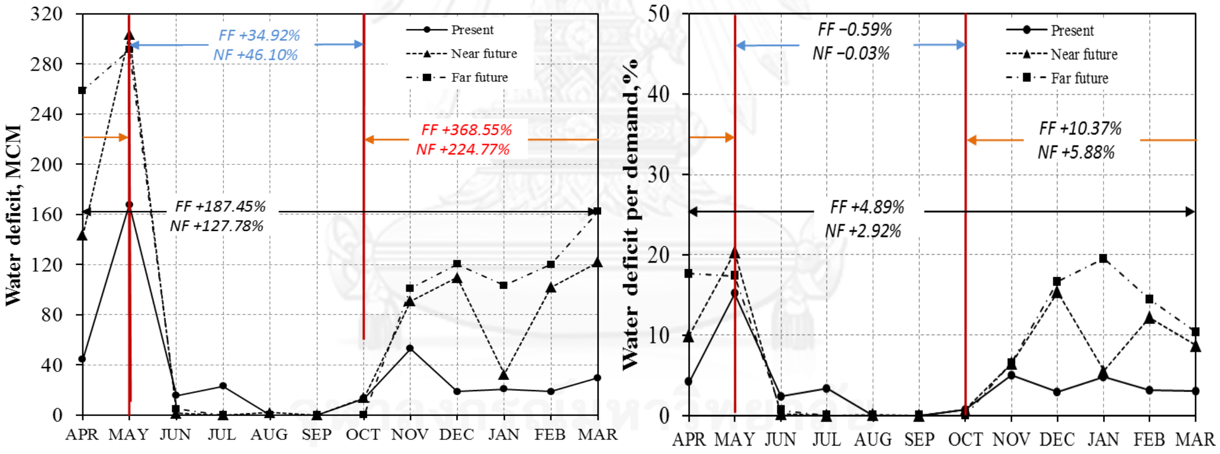
Irrigation Project	Statistics	Actual (28 years)			Present (28 years)			Near future (25 years)			Far future (25 years)		
		Wet	Dry	Annual	Wet	Dry	Annual	Wet	Dry	Annual	Wet	Dry	Annual
Phitsanulok	Mean (MCM)	17	44	60	16	142	158	10	153	163	12	154	166
	Maximum (MCM)	195	214	314	56	263	319	34	333	334	46	348	351
	Average percentage of water deficit per water demand (%)	6.07	11.67	8.87	8.09	21.42	14.76	5.67	21.14	13.40	6.56	19.15	12.85
	Maximum percentage of water deficit per water demand (%)	55.54	44.46	42.39	20.89	35.70	27.83	13.25	38.86	22.32	15.23	36.97	23.64
	Number of water shortage (years)	15	26	27	25	27	27	20	23	23	21	23	23
	Frequency (times/season, times/year)	0.36	0.35	0.27	0.24	0.52	0.37	0.21	0.53	0.36	0.23	0.52	0.37
	Maximum of continuous water shortage year (years)	-	-	20	-	-	28	-	-	24	-	-	24
Chao Phraya	Mean (MCM)	238	266	505	219	185	404	320	600	921	296	866	1162
	Maximum (MCM)	1712	1587	2,426	1212	1021	2,232	1,336	2,080	2,940	1762	3571	5,333
	Average percentage of water deficit per water demand (%)	3.53	4.79	4.16	3.60	3.85	3.73	3.57	9.73	6.65	14.22	14.22	8.62
	Maximum percentage of water deficit per water demand (%)	29.80	62.31	31.08	16.30	32.09	24.20	9.60	30.74	19.50	56.91	56.91	34.87
	Number of water shortage (years)	12	18	20	14	13	19	15	19	22	10	18	20
	Frequency (times/season, times/year)	0.28	0.32	0.23	0.24	0.29	0.23	0.18	0.41	0.23	0.17	0.44	0.24
	Maximum of continuous water shortage year (years)	-	-	9	-	-	6	-	-	14	-	-	9

The evaluation of the extreme shortage events by flood dam operation was considered the same as the general dam operations. The extreme shortage of this operation is summarized in Table 6.14. The monthly water deficit per demand is shown in Figure 6.12. From the results, in the near future, it was found that the extreme water deficit of Phitsanulok Irrigation Project will increase in both wet and dry season, while in the far future it will decrease in wet season but it increase in dry season. Due to the rainfall in drought year cause the higher water demand especially in dry season.

For the Chao Phraya Irrigation Project, in the near future, it was found that the extreme water deficit tend to decrease in dry season but it increase in wet season (shown in Figure 6.12). Due to the higher rainfall in wet season cause the lower water demand rate. On the other hand, in the far future, it was found that the extreme water deficit tend to increase in both wet and dry season due to the higher water demand even though the reservoir release more water but it will be still insufficient to meet the water demand.



(a) Water deficit of Phitsanulok (b) Water deficit per demand of Phitsanulok



(c) Water deficit of Chao Phraya (d) Water deficit per demand of Chao Phraya

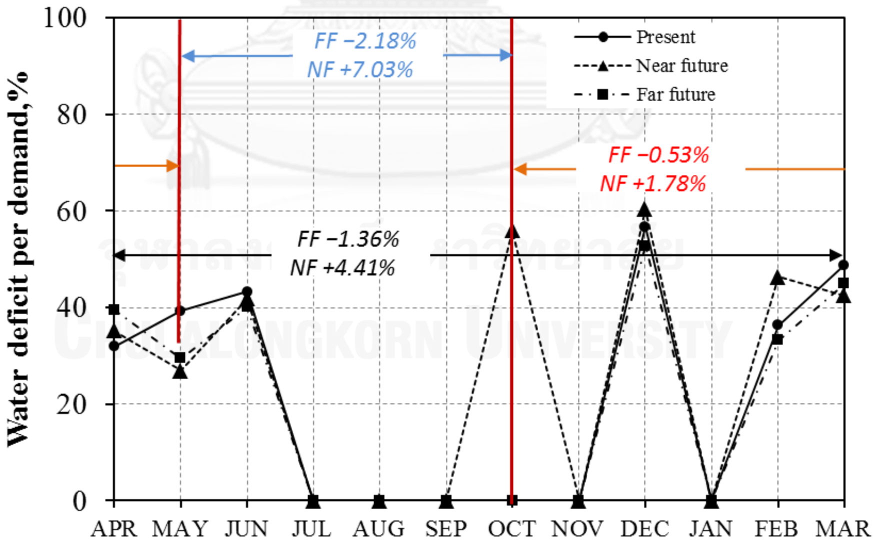
Remark : The % relative change of water deficit in NF = (Water deficit in NF - Water deficit in PR) / Water deficit in PR x 100, The % relative change of water deficit in FF = (Water deficit in FF - Water deficit in PR) / Water deficit in PR x 100,

The % relative change of water deficit per demand in NF = water deficit per demand in NF - water deficit per demand in PR, The % relative change of water deficit per demand in FF = water deficit per demand in FF - water deficit per demand in PR

Figure 6.11 Monthly mean water deficit of Phitsanulok and Chao Phraya Irrigation Project under flood dam operation

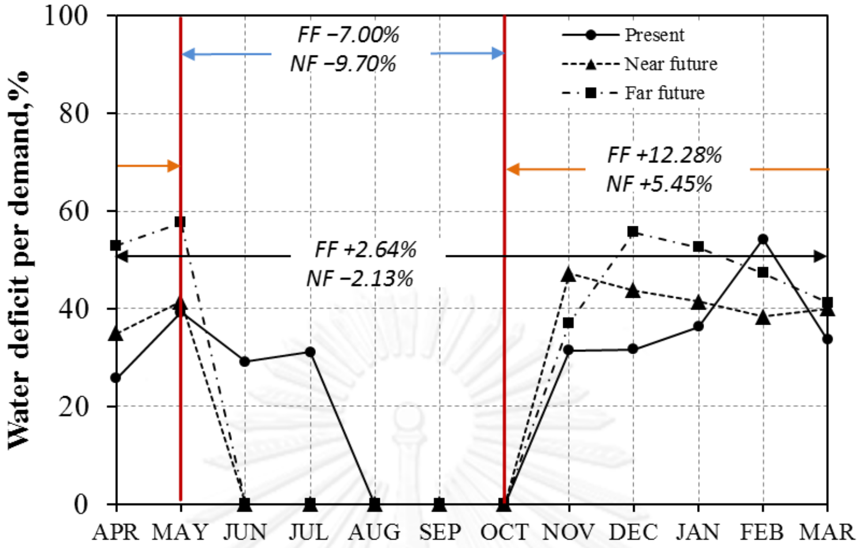
Table 6.14 Summary of the extreme shortage by flood dam operation

Project	Statistics	Observed (28 years)			Present (28 years)			Near future (25 years)			Far future (25 years)		
		Wet	Dry	Annual	Wet	Dry	Annual	Wet	Dry	Annual	Wet	Dry	Annual
Phitsanulok	Mean (MCM)	218	200	418	39	211	250	59	253	312	32	253	285
	Average percentage of water deficit per water demand (%)	51.5	39.6	45.57	13.76	28.95	21.36	20.79	30.73	25.76	11.5776	28.4201	19.9989
	Number of water shortage (years)	9	21	25	6	18	25	3	18	23	4	16	22
Chao Phraya	Mean (MCM)	1239	2200	3440	844	1448	2292	606	2660	3266	1034	3068	4103
	Average percentage of water deficit per water demand (%)	23.6	44.9	34.28	16.60	35.52	26.06	6.90	40.97	23.94	9.61	47.81	28.71
	Number of water shortage (years)	6	8	10	3	4	7	10	14	19	6	16	19



(a) Phitsanulok Project

Figure 6.12 Water deficit per demand of Phitsanulok and Chao Phraya Irrigation Project under flood dam operation in extreme case



(b) Chao Phraya Project

Remark : The % relative change of water deficit per demand in NF = water deficit per demand in NF - water deficit per demand in PR, The % relative change of water deficit per demand in FF = water deficit per demand in FF - water deficit per demand in PR

Figure 6.12 Water deficit per demand of Phitsanulok and Chao Phraya Irrigation Project under flood dam operation in extreme case (continued)

6.3.5 Stream flow at the control points

In the near future, the seasonal stream flow in the wet season will increase by 1.43% to 6.92% compared with present period while the seasonal stream flow in the dry season will not change significantly (-0.69% to 4.27%). In the far future, the seasonal stream flow in the wet season will increase by 6.10% to 9.57% in relation to the present period, while the seasonal stream flow in the dry season will increase by 5.28% to 9.66% in relation to present period.

In the near future, the annual stream flow at the control points will not change significantly (0.65% to 4.52%) while the annual runoff in the far future will increase by 5.82% to 8.64%. The higher rainfall in the far future will cause a higher runoff in the Upper and Lower Nan River Basin and the flood dam operations will cause a higher release from Sirikit Dam. A summary of the seasonal and annual stream flow at the control points is shown in Table 6.15.

Table 6.15 Summary of seasonal and annual stream flow at the control points under flood dam operation

Control point	Present			Near future			Far future		
	Wet (MCM)	Dry (MCM)	Annual (MCM)	Wet (MCM)	Dry (MCM)	Annual (MCM)	Wet (MCM)	Dry (MCM)	Annual (MCM)
N.12A	3149	3585	6734	3211	3738	6949	3385	3931	7316
Change (%)	-	-	-	1.97	4.27	3.20	7.47	9.66	8.64
N.60	4249	4210	8459	4324	4322	8646	4541	4559	9100
Change (%)	-	-	-	1.76	2.67	2.21	6.87	8.29	7.58
N.27A	3072	2611	5683	3122	2650	5773	3347	2777	6124
Change (%)	-	-	-	1.62	1.53	1.58	8.94	6.38	7.77
N.5A	4695	3046	7742	4845	3074	7919	5145	3251	8396
Change (%)	-	-	-	3.20	0.89	2.29	9.57	6.72	8.45
N.7A	6860	3854	10713	6958	3825	10783	7278	4059	11337
Change (%)	-	-	-	1.43	-0.76	0.65	6.10	5.32	5.82
N.67	10564	4878	15443	11295	4845	16140	11486	5136	16622
Change (%)	-	-	-	6.92	-0.69	4.52	8.72	5.28	7.64
C.2	15534	9488	25022	16284	9506	25790	16484	10203	26688
Change (%)	-	-	-	4.83	0.19	3.07	6.12	7.53	6.66

In near future, it was revealed that for the majority of the runoff stations the maximum accumulative runoff will decrease by 14% to 47% compared with the present period. A higher change of runoff will occur at N.60 (-46.87%).

In the far future, for the majority of runoff stations, the maximum accumulative runoff will decrease by 7% to 37% compared with the present period, except for N.7A, which will tend to increase by 17%. From the results it can be implied that flood events under flood dam operations in the near and far future will decrease in terms of magnitude and frequency and the flood peak will be reduced along the Nan River Basin. A summary of the maximum accumulative runoff under flood dam operations is shown in Table 6.16. Additionally, the probability of maximum accumulative runoff at the C.2 runoff station reveals that the magnitude of runoff will be higher, especially the mostly probability of runoff will increase is shown as Figure 6.13.

Table 6.16 Summary of maximum accumulative runoff under flood dam operation

Control point	Maximum capacity (MCM)	Maximum accumulative runoff (MCM)				Number of flood event (year)			
		Obs	P	NF	FF	Obs	P	NF	FF
N.12A	2756	4491	5046	2882	3172	2	2	1	3
N.60	3825	5549	7130	3788	4766	2	4	0	1
N.27	2916	5701	4606	2661	4124	5	3	0	2
N.5A	4804	8230	6795	4284	6343	4	4	0	2
N.7A	6147	10793	8198	6364	9614	7	7	3	2
N.67	7801	12904	16368	13419	13629	10	13	15	16
C.2	12087	26485	28560	24527	19953	7	9	9	11

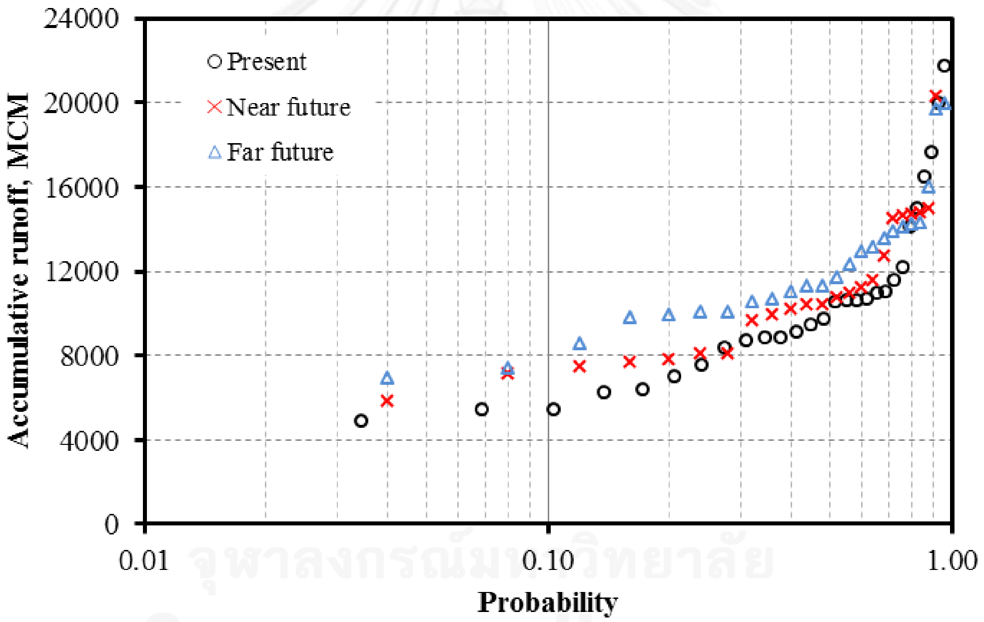


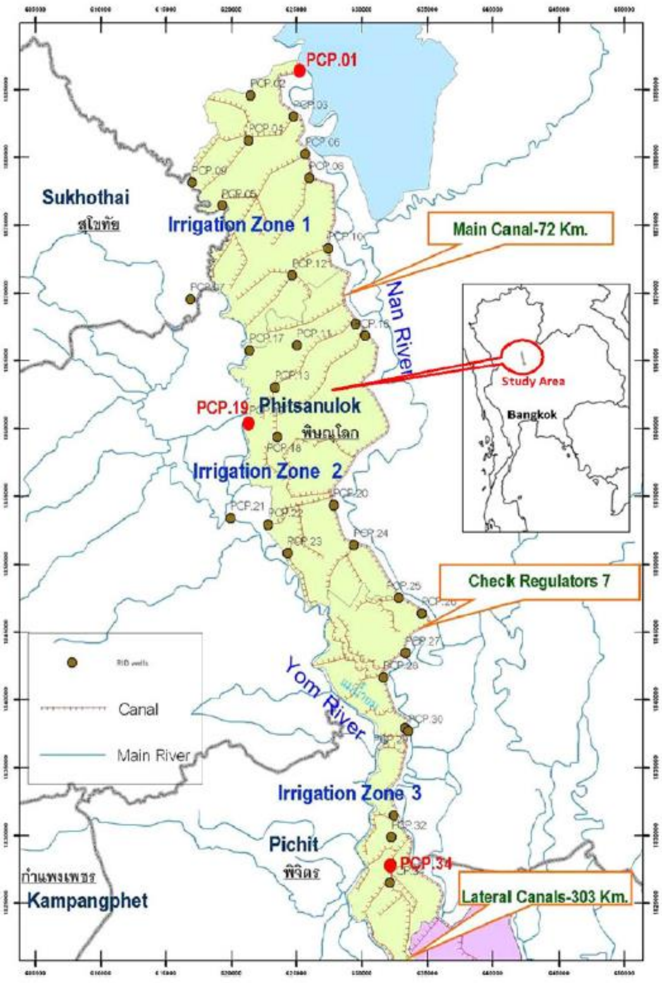
Figure 6.13 Probability of accumulative runoff at C.2 under flood dam operation

6.4 Impact assessment of the Plaichumphol Irrigation Project

The impact assessment of the Plaichumphol Operation and Maintenance Project was used to investigate the impact of dam operations on the sub-scale of the irrigation project. The Plaichumbol Irrigation Project was selected to be case study area as shown in Figure 6.14. Because this irrigated project is the largest project in the Phitsanulok Irrigation Project (PSK), which has a cultivated area of 215,768 rais and is affected directly by Sirikit Dam. In the past, this project experienced an extreme water shortage, especially between 1993 and 1994. Consequently, the impact assessment of this project will use only general reservoir operation as a case study. Regarding the impact assessment method, the water balance model was adopted to calculate the water deficit and the number of shortages in this area.

The water allocation was extracted from the results of the water balance in each dam operation to set as the water budget of irrigated project. Furthermore, the water demand was estimated from the water demand unit multiplied by the crop cultivation area using the probability classification tree method. The water deficit was calculated from the water allocation minus the water demand.

Regarding the water deficit per demand of Plaichumphol O&M Project, in the near future, the water deficit per demand in the wet season will decrease by -2.23%; however, a greater water deficit will occur in September with an increase of 1.98%. The water deficit per demand in the dry season will not change significantly (-0.19%); however, a greater water deficit per demand will occur in March by 6.01% (as shown in Table 6.17 and Figure 6.16).



source: Potential Groundwater Study of Plaichumpol Irrigation Project, 2008

Figure 6.14 Boundary of Plaichumbol Irrigation Project

In the far future, the water deficit per demand in the wet season will decrease not significantly (-0.33%) and a greater water deficit per demand will occur in October with an increase of 13.60%. On the other hand, the water deficit per demand in the dry season will not change significantly; however, a greater water deficit per demand will occur in March by 9.51% (as shown in Table 6.17 and Figure 6.16).

The annual water deficit per demand in the near future will decrease by 10.64% while the annual water deficit per demand in the far future will not change significantly (-2.32%).

Table 6.17 Summary of water balance in Plaichumphol O&M Project

Variable	Statistics	Present (28 years)			Near future (25 years)			Far future (25 years)		
		Wet	Dry	Annual	Wet	Dry	Annual	Wet	Dry	Annual
Water allocation	Mean (MCM)	206	221	426	204	233	438	194	236	430
	Maximum (MCM)	375	358	733	363	410	773	388	401	789
Water demand	Mean (MCM)	94	202	295	90	227	317	90	236	327
	Maximum (MCM)	126	253	379	147	266	413	165	287	452
Water deficit	Mean (MCM)	4	29	33	3	37	40	6	40	46
	Maximum (MCM)	34	100	133	35	98	134	40	107	147
Water deficit per demand	Mean (%)	7.15	15.62	11.39	4.92	15.43	10.17	6.81	15.43	11.12
	Maximum (%)	31.04	44.55	37.80	20.90	38.97	29.93	31.08	37.68	34.38
Number of water shortage		28	28	28	21	25	25	22	25	25

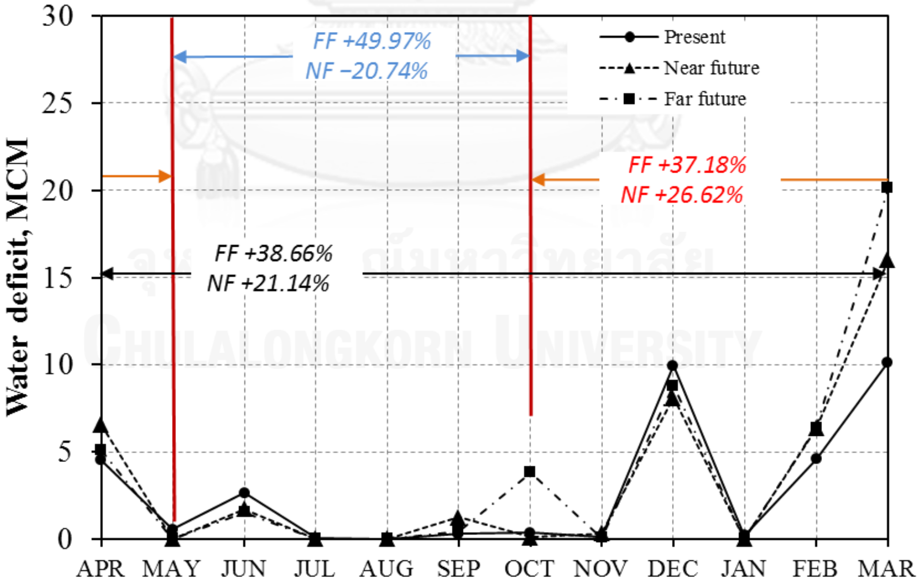
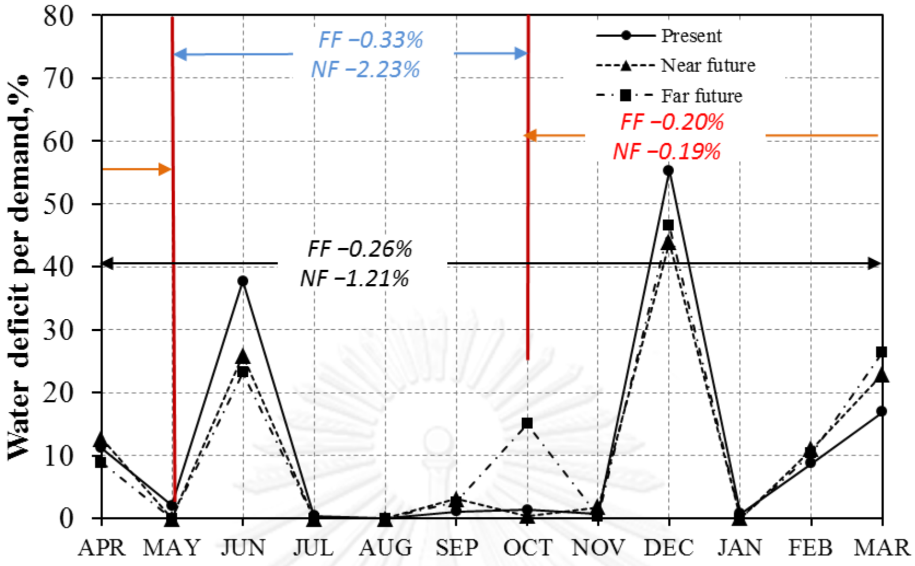


Figure 6.15 Monthly mean water deficit of Plaichumphol Operation and Maintenance Project under general dam operation



Remark : The % relative change of water deficit per demand in NF = water deficit per demand in NF - water deficit per demand in PR, The % relative change of water deficit per demand in FF = water deficit per demand in FF - water deficit per demand in PR

Figure 6.16 Monthly water deficit per demand of Plaichumphol Operation and Maintenance Project under general dam operation

6.5 Summary of the impact assessment on the existing dam operation

Regarding the results of reservoir operation and impact assessment can be summarized in the term of the impact of reservoir release rule and the climate change as follows.

6.5.1 Impact of reservoir release rule

The impact of reservoir operation rule can be summarized as follows.

1) The water demand which affected from the water demand decision module reveals that the general reservoir operation provided higher water demand compared with the flood reservoir operation.

2) The portion of seasonal storage under general reservoir operation is about 0.40:0.60 (wet storage : dry storage) and the portion of seasonal release is about 0.42: 0.58. On the other hand, the portion of seasonal storage under

flood reservoir operation is about 0.38:0.62 (wet storage : dry storage) and the portion of seasonal release is about 0.44: 0.56.

3) The water shortage event will have the more chance to occur in Chao Phraya Irrigation Project in both reservoir operations. The flood reservoir operation will yield the greater water deficit than the general reservoir operation.

4) The spillage of Sirikit Dam in the near and far future will not occur in the flood reservoir operation but the spillage will occur in the general reservoir operation.

5) The seasonal and annual stream flow under the flood reservoir operation will tend to increase in mostly control points compared with the general reservoir operation.

6) The maximum accumulative runoff in the near and far future under flood reservoir operation will decrease at the control point N.60, N.27 and N.27, while it will increase at the control point N.12A, N.7A, N.67 and C.2. On the other hand, the maximum accumulative runoff under general reservoir operation will tend to decrease at the control point N.12A, N.7A, N.67 and C.2. , while it will increase at the control point N.60, N.27 and N.27.

6.5.2 Impact of climate change

The impact assessment on the existing dam operation can be summarized in Table 6.18.

Table 6.18 Summary of the impact assessment on the existing dam operation

Reservoir operation	Irrigation Project	Change in near future (%)			Change in far future (%)		
		Wet	Dry	Annual	Wet	Dry	Annual
General	PSK water demand	↓-3.04	↑16.18	↑10.28	↓-3.52	↑21.17	↑13.59
	CHY water demand	↑11.13	↑16.32	↑13.40	↓-2.86	↑21.38	↑7.76
	Inflow	↑6.44	↑0.74	↑5.64	↑12.64	↑7.56	↑11.93
	Storage	↑8.34	↑7.66	↑7.93	↑13.55	↑12.16	↑12.7
	Release	↑5.98	↑8.18	↑4.74	↑13.62	↑11.01	↑9.53
	Maximum spillage	-	-	↑3.18	-	-	↑18.47
	PSK Water deficit per water demand	↓-0.26	↓-0.13	↓-0.19	↑2.18	↓-0.10	↑1.04
	PSK Number of water shortage	0.00	↓-14.81	↓-14.81	↑50.00	↓-14.81	↓-14.81
	CHY Water deficit per water demand	↑0.21	↑6.84	↑3.53	↓-0.98	↑4.32	↑1.67
	CHY Number of water shortage	↑28.57	↑50.00	↑40.00	↓-28.57	↑42.86	↑33.33
	Maximum accumulative runoff	-	-	↓-34.65	-	-	↓-71.13
	Number of flood event	-	-	-83.3 - 50	-	-	-16.7 - 150
Flood	PSK water demand	↓-0.96	↑14.88	↑10.06	↓-1.10	↑19.45	↑13.09
	CHY water demand	↑22.56	↑25.48	↑23.85	↑3.33	↑15.47	↑8.71
	Inflow	↑6.44	↑0.74	↑5.64	↑12.64	↑7.56	↑11.93
	Storage	↑2.19	↑3.82	↑3.2	↑3.62	↑7.07	↑5.75
	Release	↑6.36	↑7.33	↑4.51	↑12.45	↑12.82	↑10.14
	Maximum spillage	-	-	-	-	-	-
	PSK Water deficit per water demand	↓-2.42	↓-0.29	↓-1.36	↓-1.54	↓-2.27	↓-1.91
	PSK Number of water shortage	↓-20.00	↓-14.81	↓-14.81	↓-16.00	↓-14.81	↓-14.81
	CHY Water deficit per water demand	↓-0.03	↑5.88	↑2.92	↓-0.59	↑10.37	↑4.89
	CHY Number of water shortage	↑7.14	↑46.15	↑15.79	↓-28.57	↑38.46	↑5.26
	Maximum accumulative runoff	-	-	↑32.75	-	-	↓-54.41
	Number of flood event	-	-	-100 - 15.4	-	-	-75 - 50

CHAPTER VII

ADAPTIVE RESERVOIR OPERATION

The adaptive reservoir operation system was developed for responding to the impact of future climate change. This chapter includes a discussion of adaptive reservoir operation development, model calibration and verification and the adaptive reservoir operation results and their application.

7.1 Adaptive reservoir operation development

There are four modules in the developed system; namely the reservoir operation module, the water demand and water release decision-making module, and the water resources balance module. The first module applies the water balance concept to simulation of the physical system for reservoir operations. The engine for deriving reservoir release is in the second module, which was developed based on the Adaptive Network Based Fuzzy Inference System (ANFIS) techniques. The reservoir operation model is a combination of water demand decision-making module, the release decision-making module and the reservoir operation module. The model was run using inputs from the database (hydrological data and characteristics of reservoir) along with the estimated inflow, lateral flow, rainfall downstream and water demand. The results obtained from the reservoir operation model were evaluated in the fourth module, the water network balance module, using two indicators; namely, the magnitude of water deficit and spillage. The components of adaptive reservoir operation and data transferring process were shown as Figure 7.1.

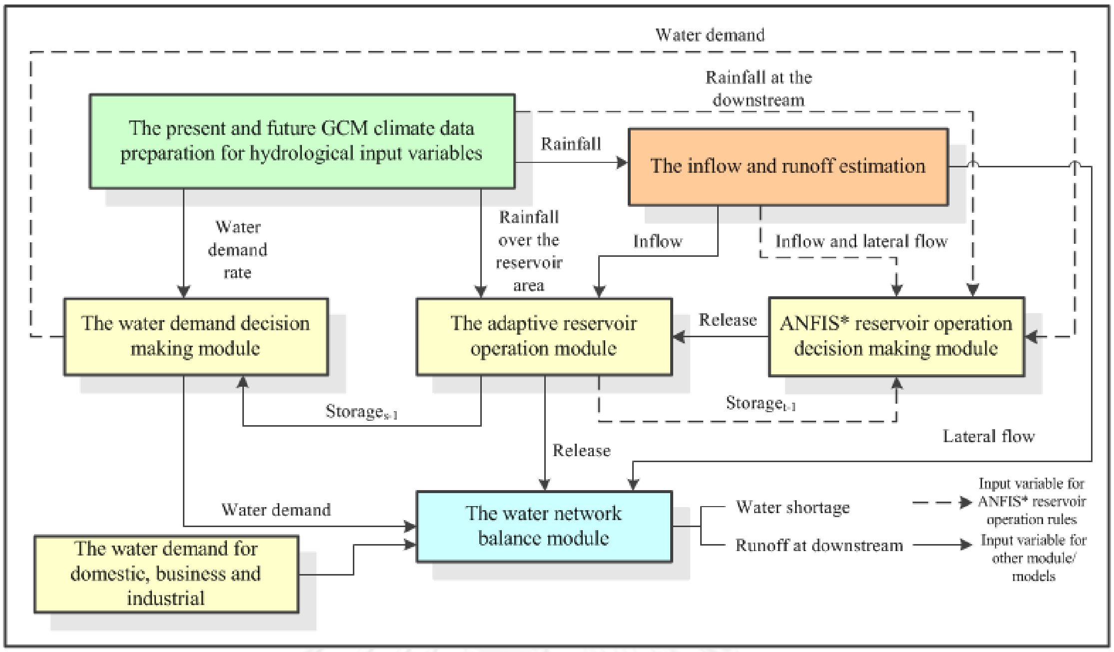


Figure 7.1 The components of adaptive reservoir operation and data transferring process

The release decision-making processes were developed in this study for the ANFIS reservoir operation model based on the probability classification tree and the neurofuzzy modeling approach. The decision-making process was based on the switch control or storage state condition. The switch control was used for selecting the type of reservoir operation. The reservoir operation types were considered in accordance with the antecedent storage. The monthly data of inflow to the reservoir and rainfall at the downstream, lateral flow and water demand for 1987 to 1996 were used for model calibration.

The water demand decision-making module adopted the probability classification tree approach which classified the antecedent effective storage from the historical data. The type of water season was identified at the end of the season, and then the crop cultivation area according to the water season was set up. Thus, the crop requirement was classified according to antecedent effective storage from the historical cultivated area. Next, this module took up the crop cultivation area to multiply with the water demand rate (see details in Chapter 6.1 and Appendix D.1.6).

The release decision-making module adopted the Adaptive Network Based Fuzzy Inference System (ANFIS) which trained the release rules by ANFIS toolbox in the MATLAB programming. The trained data included inflow, lateral flow, rainfall downstream, and water demand and release. Hence, there were 8 main release rules which selected rule according to the switch control or storage state condition.

The adaptive dam operation module was developed using the MATLAB language programing. Hence, this model programing was shown the details in Appendices G. The procedures are as follows:

1) Collect the reservoir operation data of Sirikit Dam for 1979 – 2012 e.g. inflow, release and storage.

2) Create the probability of the antecedent effective storage and determine the water season, set up the water season in the wet and dry season, and then classify the state variables for training the ANFIS release functions included the input and output variables by using the probability decision tree method.

3) Develop ANFIS water release decision making rules by calibrating and verifying the model with the actual dam operation.

4) Develop a water demand decision-making module by using the probability decision tree method to classify from the storage at the end of the season and estimate the water demand rate based on the climate condition (see detail in Appendix D.1.6).

5) Develop a reservoir water balance module by using the storage balance concept.

6) Develop a water network balance module by calibrating and verifying the model with the observed runoff (see details in Appendix F).

7) Develop an ANFIS dam operation model by integrating the ANFIS water release decision-making rules, the water demand decision-making module, the reservoir water balance module, and the water network balance module.

8) Explore the capability of ANFIS reservoir operations.

9) Modify the ANFIS reservoir operation model (called ANFIS*) and calibrate for suitable membership functions by adjusting the general dam operations to minimize water deficit and spillage.

10) Apply the ANFIS* dam operation model by using the GCM hydrological input variables.

The goodness of fit test was used to test the performance of the reservoir operation rules that included the correlation of determination (R^2), the root mean square error, and the standard error. Hence, the simulated release was compared with the observed release in the calibration and verification period. The initial antecedent storage was the observed value of antecedent storage (the calibration and verification results are shown in Appendices F.

7.2 ANFIS reservoir operation components

The Adaptive Network Based Fuzzy Inference System (ANFIS) approaches adopted for the model development of the reservoir operation are presented in this section. The optimization of the fuzzy inference system including premise and consequent parameters values, was determined through neurofuzzy computing using available data. In the neurofuzzy modeling approach, the number of membership functions is identified prior to initiating the process for its computing. The number of fuzzy rules, depending on the specified membership functions for each input variable, is significantly increased if the number of input variables increases. Hence, the system becomes complex with more variables, and its optimal number of membership functions is difficult to determine from a large searching space. The ANFIS release decision making concept is shown in Figure 7.2.

The ANFIS dam operation model is composed of the dynamic system simulation and the adaptive neurofuzzy inference system in order to determine the amount of the water to be released from the reservoir under uncertain conditions (see detail in D.1.2). This model includes 5 parts as follows:

Part 1: The input variables include the initial storage (S_{ti}), the inflow (I_t), sideflow (S_F), rainfall in the downstream basin (R_t) and water demand (W_{dt}).

Part 2: The reservoir water balance process, which adopts the water storage concept. This process will receive the input variables and water release decision-making module (see detail in D.1.2).

Part 3: The ANFIS water release decision-making process includes fuzzification, inference, and defuzzification. Fuzzification uses the membership function to represent the uncertainty of the input variables by applying rule base (IF-THEN). The inference is the decision-making logic to decide release from reservoir. While the defuzzification transforms the uncertain amount to the values, and then sends the values to part 2.

Part 4: The water demand decision-making process which uses tree probability classification to determine the crop cultivation area depending on the storage state at the end of the season. The output will be sent to part 2 (see details in Appendix D.1.6).

Part 5: The water network balance process which calculates the water deficit by receiving the release values from part 3 and the water demand from part 4, respectively (see details in Appendix F).

7.3 The functional of the ANFIS dam operation module

The function of the ANFIS dam operation module is as follows:

1) The reservoir water balance process uses the storage balance to find out the storage (S_t) that receives the monthly data from the input variables

process and includes the inflow, and rainfall and evaporation, and receives the initial storage and release from the ANFIS water release decision-making process.

2) The ANFIS water release decision-making process can be separated into 8 release rules based on the antecedent effective storage (S_{t-1}). This process will receive the input variables from the other process, including the inflow (I_t), sideflow (S_F) and rainfall in the downstream basin (R_t) from the input variables process, the water demand from the water demand decision-making process, and the antecedent effective storage (S_{t-1}) from the reservoir water balance process.

3) The water demand decision-making process can be separated into 8 release rules based on the effective storage at the end of the season. This process will receive the effective storage at the end of the season to determine the crop cultivation area and this area is multiplied by the water demand rate.

4) The water network balance process calculates the water deficit of the irrigation projects. This process will receive the release from the reservoir water balance process and water demand from the water demand decision-making process.

7.4 ANFIS release decision making development

The ANFIS release decision-making determines the ANFIS release functions according to the storage state as follows:

1) Determine the input and output variables Hence, the input variables include antecedent effective storage (S_{efft-1}), inflow (I_t), sideflow (S_F), rainfall in the downstream basin (R_t) and water demand (W_{dt}); the output variable is release (O_t).

2) Create the probability of antecedent effective storage and determine the water season, and then define the type of water season in wet or dry season.

3) Classify the state variables for training the ANFIS release functions including the input and output variables by using the probability decision tree method, and then classify them as high, normal, dry and very dry water seasons. The wet season begins on April 30 and the dry season begins on October 31.

4) Create an input variable file by separating them into 8 files according to the type of water season, such as: 1) high water season (2 rules), 2) normal water season (2 rules), 3) dry water season, and 4) very dry water season.

5) Generate the ANFIS by using the ANFIS toolbox in the MATLAB program.

6) Calibrate the ANFIS release functions by selecting the shape of the membership function and adjusting the membership functions to enhance the correlation and simulate the release using the reservoir operation model.

7) Verify the ANFIS release functions for testing the accuracy of the ANFIS reservoir operation model by simulating the release using the reservoir operation model.

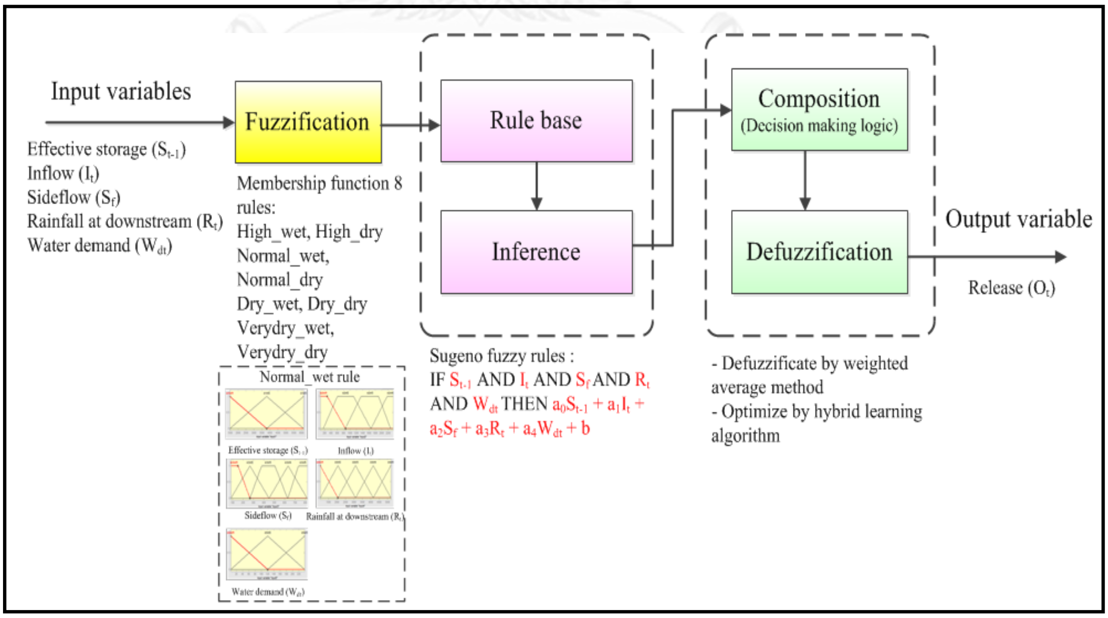


Figure 7.2 ANFIS release decision making concept

7.5 ANFIS* reservoir operation processes

The objective of this adaptive reservoir operation development is to reduce the water deficit and spillage. The adjusted ANFIS reservoir operation development is comprised of two processes: 1) modifying the general dam operations and 2) modifying the ANFIS dam operations. The modifying general dam operation improves the release rules to minimize the water deficit and spillage. Consequently, the output of modifying general dam operation will be adopted as the initiate input variables for the modified ANFIS dam operation. Regarding the modified ANFIS dam operation, the membership function rules of ANFIS will be adjusted to improve the efficiency of the ANFIS dam operation. The modified ANFIS reservoir operation will be called “ANFIS*”. The release–antecedent effective storage ratio of the general dam operation was optimized for the appropriate release. The improvement of this ratio is shown in Table D-8 and D-9. The suitable increasing percentage was considered at the minimum water deficit, minimum spillage of the reservoir, minimum number of shortage years and minimum continued shortage. Finally, the ANFIS dam operation model was calibrated by selecting the number of membership functions (MF).

1) Modify the general dam operation rule by adjusting the release – antecedent effective storage ratio to minimize the water deficit and spillage.

2) Increase the percentage of the release-storage ratio in both wet and dry season to minimize the amount of water deficit and number of water shortage years and compare the change in average monthly water deficit in each water season and according to monthly type.

2.1) Increase the percentage of the release-storage ratio in the dry season to minimize the water spillage of reservoir and compare the change in average monthly water spillage in each water season and according to monthly level type.

2.2) Find out the optimum point of release-storage ratio at the minimum water deficit and the number of water shortage years for the water shortage events; on the other hand, the optimum point of release-storage ratio was found at the minimum water spillage.

3) Classify the results of the modified general dam operation as the input and output variables based on the probability of the antecedent effective storage in the wet and dry season.

4) Establish the ANFIS* water release decision-making module based on the ANFIS* release rules.

5) Calibrate and verify the modified ANFIS release decision-making module by adjusting the membership functions to increase the correlation of release between the ANFIS* and modified general dam operations (year 1987 – 1996 for model calibration and year 1997 – 2011 for model verification).

6) Validation is the final checking step before applying this model. The recorded data for the years 1987 – 2011 were used to compare the results with the modified general dam operation.

7) Apply the reservoir operation model to assess the impact of climate change on the water balance, spillage, water shortage, and runoff.

7.6 Water network balance module

The concept of water network balance is considered the balancing between the inflow and outflow of the control point. The input variables include the release from reservoir operation module, lateral flow and water demand (see detail in Appendix F). The related water demand which set as the extraction points includes the domestic, business, industrial, irrigation and salinity pushing. The total water supply usage of Nan River Basin can be separated into domestic 10.09 MCM/year, business 4.66 MCM/year and industrial 1.36 MCM/year, respectively. The total water supply usage of Chao Phraya River Basin can be separated into domestic 728 MCM/year, business 63 MCM/year and industrial 808 MCM/year, respectively. The main large irrigation projects which focused for evaluating the impact of reservoir operation including Phitsanulok and Chao Phraya Irrigation Projects. Their irrigation area is about 666,400 rais and 7,542,822 rais, respectively. Their irrigation water demand is about 710 MCM/year and 9,878 MCM/year, respectively. Furthermore the minimum flow which release though Chao Phraya Diversion Dam such as the salinity flushing with flow rate 80 cms or 2,488 MCM/year (EGAT, 2009), the waterworks which extracted from Chao Phraya River by PWA and MWA about 1,615 MCM/year.

The water network balance of The Lower Chao Phraya River Basin is necessary to consider the water budget which supplies to the main water user such as the lateral flow from Sakaekang and Upper Chao Phraya River Basin. The constraint of water balance network is determined to supply for the salinity pushing, PWA and MWA as the first priority. These water usages will not occur the shortage event. On the other hand, the water balance module will allow the water deficit occur only in the irrigation projects.

The water supply usage can be represented in the water extraction points in the water network flowchart shown as Figure F.1. The water supply usage was grouped by the location of districts and waterworks office, it included seven PWA and one MWA extraction points. However, the other water extraction points are the medium-, small- and pumping irrigation projects which were grouped by the location of districts include five irrigation extraction points.

In the water balance analysis, It has to set up the minimum flow though Chao Phraya Diversion Dam, and then the residual water will be the water supply for the Great Chao Phraya Irrigation Project. This water supply will be taken to multiply with the water allocation ratio for Chao Phraya Irrigation Project shown as Table F.7. Hence, this water allocation ratio was calculated from the portion between water allocation and water supply from the past pattern. This water allocation was summarized from the amount of release water through the east and west Chao Phraya Irrigation Project. The accuracy of water network balance model can be validated with the actual water release shown as Figure F.3 and F.5, respectively.

7.7 Results and discussions

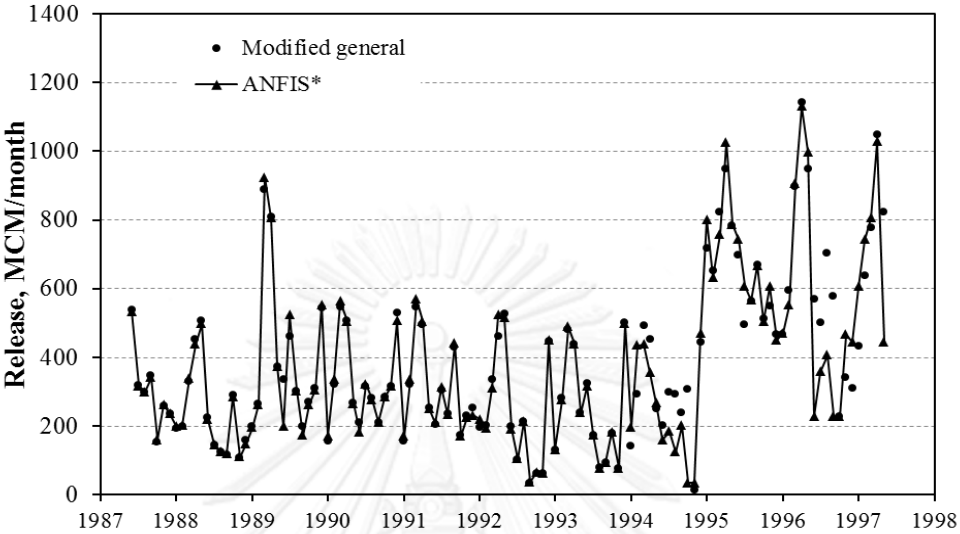
7.7.1 Model calibration and verification

In order to the results of ANFIS dam operation that reveal the higher water deficit and higher shortage compared with the actual dam operation. The solution of this problem can be solved by adjusting the release rules to respond to the water shortage and flood. Therefore the adaptive dam operation can be formulated from adjusted general dam operation. Because the general dam operation uses the release–effective storage ratios as the rules for operation, the general dam operations can be improved the efficiency by adjusting the release–effective storage ratios to minimize the water deficit, spillage and flood volume. The results from the modified general dam operation were used as the input and output variables for the ANFIS to calibrate the new release rules, called the “ANFIS*”. However, the accuracy of the ANFIS can be tested from the goodness of fit test, such as the correlation of determination, the root mean square error, and the standard error.

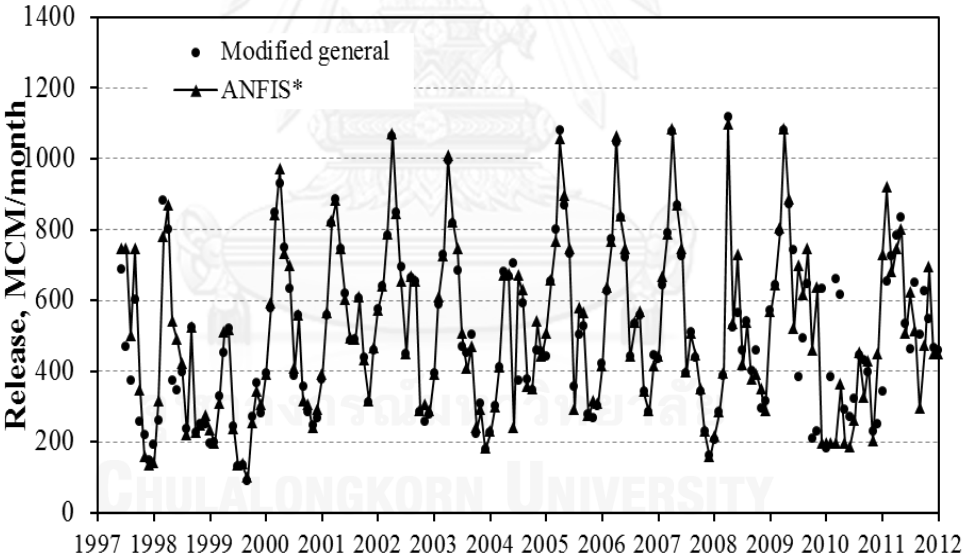
The best membership functions is the triangle membership [3,4,3,5,4]. The release of the modified general and ANFIS* were compared in order to find the goodness of fit test. The results of the model calibration and verification are shown in Table D.10. The correlation of determination (R^2) in the model calibration was 0.88, while the correlation of determination (R^2) in the model verification was 0.79. In the model calibration, the root mean square error (RMSE) and standard error of the model calibration were 51 MCM/month and 79 MCM/month, respectively. On the other hand, in the model verification, the root mean square error and standard error of model calibration were 88 MCM/month and 109 MCM/month, respectively.

For the model validation (year 1987 to 2011), the results show the correlation of determination (R^2) as 0.84. The root mean square error and standard error were 102 MCM/month and 98 MCM/month, respectively.

A comparison of the monthly release of the modified general and ANFIS* in model calibration and verification is shown in Figure 7.3.



(a) Model calibration period (1987 – 1996)



(b) Model verification period (1997 – 2011)

Figure 7.3 Comparison of release under modified general and ANFIS* dam operation

The storage and release of Sirikit Dam by actual, general, flood and ANFIS* reservoir operation in the validation period (1987 – 2012) are shown as Figure 7.4 and 7.5. Figure 7-4 reveals the storage of the ANFIS* located between general and flood reservoir operations from August to March, the storage of the ANFIS* in the wet season and dry season was lower than actual dam operation at 8.89% and 6.96%, respectively. The annual storage was lower than actual dam operations at 6.96%.

The results show that this ANFIS* will release more water in the wet season (16.86%) especially from May to August, while in the dry season it will release less water (-2.31%). The annual release is higher than the actual dam operation at 7.27%.

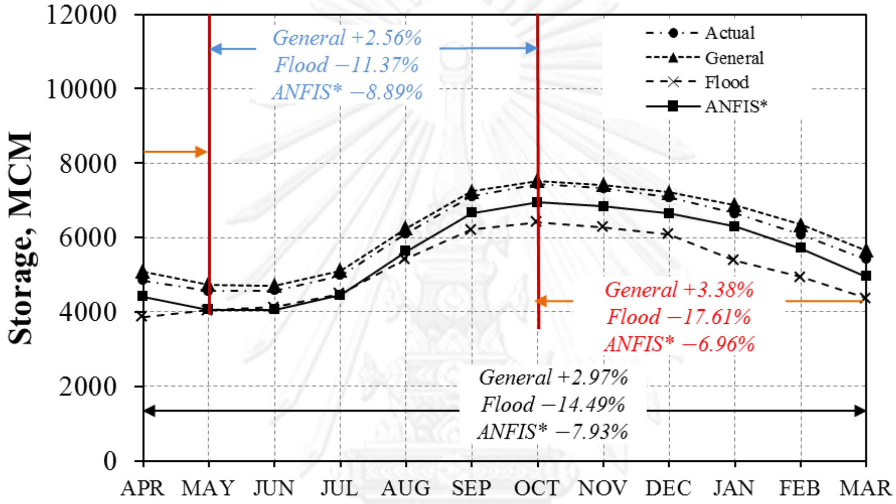


Figure 7.4 Storage of Sirikit Dam by actual, general, flood and ANFIS* reservoir operation in validation period (1987 – 2012)

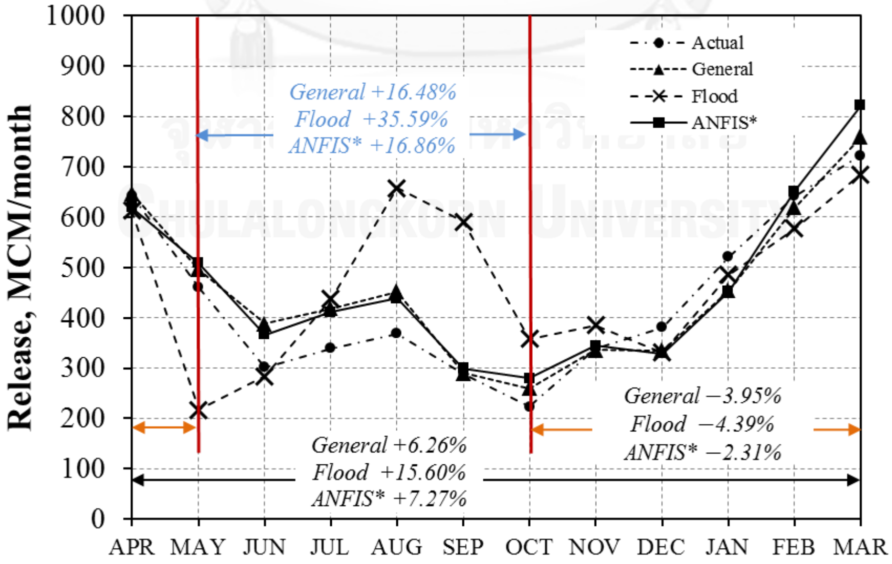


Figure 7.5 Release of Sirikit Dam by actual, general, flood and ANFIS* reservoir operation in validation period (1987 – 2012)

The comparison of the maximum spillage among actual, general, flood and ANFIS* reservoir operations for the validation period (1987 – 2012) revealed that ANFIS* can reduce the spillage efficiently (-12%), as shown in Figure 7.6. The results show that the annual water deficit per demand of the ANFIS* for the Phitsanulok Irrigation Project will decrease by -24.52% as shown in Figure 7.7.

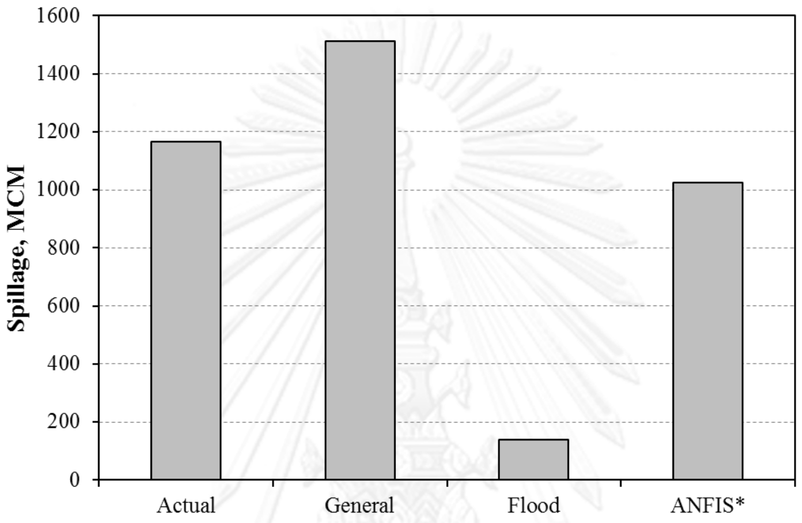


Figure 7.6 Spillage of Sirikit Dam by ANFIS* reservoir operation in validation period (1987 – 2012)

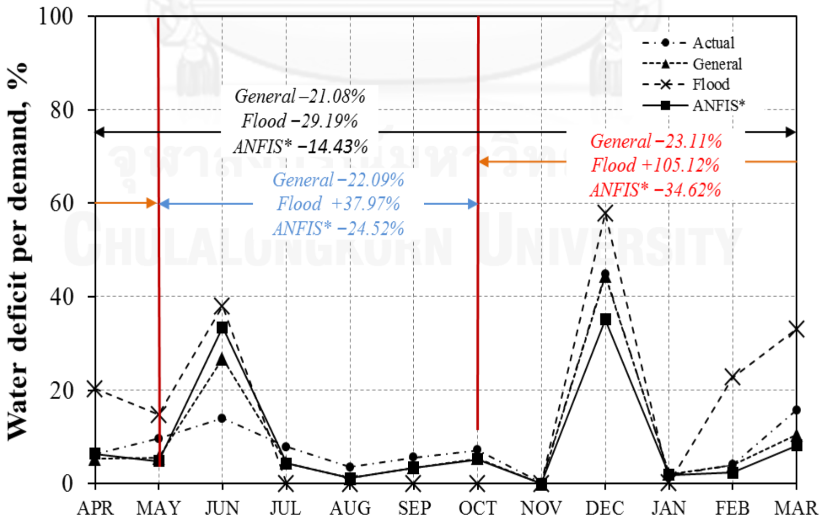


Figure 7.7 Water deficit per demand of Phitsanulok Irrigation Project by ANFIS* dam operation in validation period (1987 – 2012)

7.7.2 Comparison of the efficiency of reservoir operation system

The efficiency of reservoir operations can be evaluated by comparing the results of the reservoir operation from each method. Therefore, the comparison based on the historical input variables in 1979 – 2012. The objective of the comparison is to investigate the effect of model developed components. The storage and release of each reservoir operation would be compared with the actual reservoir operation. The detail of efficiency evaluation is shown as Appendix D.2.6.

Regarding the reservoir operations development processes, the reservoir operations system was developed based on the formulating of release rule, the water demand decision making module, the ANFIS* with water demand as a input variable, the ANFIS* with lateral flow as a input variable and the ANFIS* with water demand and lateral flow as input variables. Furthermore, the efficiency of reservoir operation also can be evaluated by comparing the results of reservoir operation with present GCM input variables. The cases of reservoir operation system and the condition were summarized in Table 7.1. The reservoir operations can be separated into 13 cases for comparing in each issue as follows. The summary of efficiency evaluation was shown in Table 7.2.

Table 7.1 The cases of reservoir operation for evaluating the efficiency

Case	Reservoir operation	Condition
Case 1	Actual release	Use all observed input variables
Case 2	General release rule	Use all observed input variables except release
Case 3	Flood release rule	Use all observed input variables except release
Case 4	ANFIS* release rule	Use all observed input variables except release
Case 5	General release rule with water demand module	Use all observed input variables except release and water demand
Case 6	Flood release rule with water demand module	Use all observed input variables except release and water demand
Case 7	ANFIS* release rule with water demand module	Use all observed input variables except release and water demand
Case 8	ANFIS* release rule with water demand as a input variable	Use all observed input variables except release and water demand
Case 9	ANFIS* release rule with lateral flow as a input variable	Use all observed input variables except release and water demand
Case 10	ANFIS* release rule with water demand and lateral flow as the input variables	Use all observed input variables except release and water demand
Case 11	General release rule with water demand module with GCM input variables	Use all present GCM input variables except release and water demand
Case 12	Flood release rule with water demand module with GCM input variables	Use all present GCM input variables except release and water demand
Case 13	ANFIS* release rule with water demand module with GCM input variables	Use all present GCM input variables except release and water demand

Table 7.2 Summary of efficiency evaluation

Case	Overview summary		
	Storage and release	Water demand	Water deficit per demand
Case 2	Storage increase in wet season but decrease in dry season ; storage higher than case 3 and 4; release increase in wet season but decrease in high water season while release vary in dry season, release higher than case 4 but lower than case 3	Not change from case 1	Water deficit per demand of PSK decrease in wet season while vary in dry season -1.71% to 0.70%; Water deficit per demand of CHY decrease in wet season except very dry water season, while decrease -30.93% to -1.14% in dry season. Water deficit per demand decrease lower than case 3 but higher than case 4.
Case 3	Storage increase in wet season and decrease in dry season; storage lower than case 2 and 4; release increase in wet and dry season; espeacially in very dry water season; release higher than case 2 and 4 in wet season while release higher than case 2.	Not change from case 1	Water deficit per demand of PSK vary in wet and dry season. Water deficit per demand of CHY vary in wet season but decrease in dry season, water deficit per demand increase higher than case 2 and 4 except lower in very dry water season.
Case 4	Storage increase in wet season but decrease in dry season; release decrease in wet season except in very dry water season increase but increase in dry season; release higher than case 2 but lower than case 3.	Not change from case 1	Water deficit per demand of PSK decrease in wet season except normal season increase, while decrease in dry season except very dry season increase. Water deficit per demand of CHY vary in wet season but decrease in dry season, water deficit per demand decrease lower than case 2 and 3 except in high and normal water season lower than case 3.
Case 5	Storage increase in wet season but decrease in dry season ; storage higher than case 3 and 4; release increase in wet season but decrease in high water season while release vary in dry season, release higher than case 4 but lower than case 3	Water demand of PSK decrease in wet season but vary in dry season, Water demand of CHY increase in wet and dry season.	Water deficit per demand of PSK vary in wet and dry season; Water deficit per demand of CHY decrease in wet and dry season except normal water season.

Table 7.2 Summary of efficiency evaluation (continued)

Case	Overview summary		
	Storage and release	Water demand	Water deficit per demand
Case 6	Storage will not change from case 3	Water demand of PSK decrease in wet season but vary in dry season, Water demand of CHY increase in wet and dry season except high season decrease.	Water deficit per demand of PSK increase in wet season except very dry water season decrease, it vary in dry season. Water deficit per demand of PSK is higher than case 5 and 7 in normal water season. Water deficit per demand of CHY vary in wet and dry season.
Case 7	Storage increase in wet season but decrease in dry season; Release vary in wet season but increase in dry season; release closer to case 5 except very dry water season release more water than case 5.	Water demand of PSK decrease in wet season but vary in dry season, Water demand of CHY increase in wet and dry season.	Water deficit per demand of PSK vary in wet season but decrease in dry season. Water deficit per demand of CHY decrease in wet and dry season. Water deficit per demand of CHY is lower than case 5 except in very dry water season.
Case 8	Storage is lower than case 7 in wet and dry season around 2%. Release is higher than case 7 in dry season around 5% - 7%.	Water demand of PSK is closer to case 7 while water demand of CHY is higher 2% - 4% than case 7except lower in normal water season.	Water deficit per demand of PSK is lower than case 7 in both wet and dry season.
Case 9	Storage is lower than case 7 in wet and dry season around 1-2%. Storage is higher than case 8. Release is higher than case 7 in dry season around 5% - 7%.	Water demand of PSK is equal to case 8 water demand of CHY is higher 3% except lower 1.2% in normal water season.	Water deficit per demand of PSK and CHY are lower than case 7, 8 and 9 in both wet and dry season.
Case 10	Storage is higher than case 7, 8 and 9 especially in high water season but the other season in lower than case 7. Release is lower than case 7 in wet eason, but release is higher in dry season in the other water season.	Water demand of PSK and CHY are closer to case 7.	Water deficit per demand of PSK and CHY are lower than case 7, 8 and 9 in both wet and dry season.

Table 7.2 Summary of efficiency evaluation (continued)

Case	Overview summary		
	Storage and release	Water demand	Water deficit per demand
Case 11	Storage is higher in wet season, while it is lower in dry season compared with case 1. Very dry water season does not occur in this case. Release is higher in both wet and dry season except lower in wet season in high water season compared with case 1.	Water demand of PSK and CHY vary in wet season, while is higher in dry season compared with case 1.	Water deficit per demand of PSK is higher in both wet and dry season, while water deficit per demand of CHY is lower in both wet and dry season compared with case 1.
Case 12	Storage is higher in wet season, while it is lower in dry season compared with case 1. The storage in normal water season is lower than case 11 but in dry water season in higher than case 11. High and Very dry water season do not occur in this case. Release is higher in both wet and dry season except lower in wet season in high water season compared with case 1.	Water demand of PSK and CHY vary in wet season, while is higher in dry season compared with case 1.	Water deficit per demand of PSK is higher in wet season but vary in dry season, while water deficit per demand of CHY is lower in both wet and dry season compared with case 1.
Case 13	Storage is higher in wet season, while it is lower in dry season compared with case 1. Release is higher in both wet and dry season except lower in wet season in very dry water season compared with case 1.	Water demand of PSK is lower in wet season but it is higher in dry season compared with case 1. Water demand of CHY is lower in normal water season, but it is higher in dry water season compared with case 1.	Water deficit per demand of PSK is higher in wet season but vary in dry season, while water deficit per demand of CHY is lower in both wet and dry season compared with case 1.

7.7.3 ANFIS* reservoir operation application

The ANFIS* dam operation can be applied to the evaluation of the effectiveness of climate change adaptation via the irrigation water demand, reservoir water balance, water shortage, spillage, and maximum accumulative runoff. The impact was compared with the results from the existing reservoir operation and ANFIS* dam operation.

7.7.3.1 Irrigation water demand

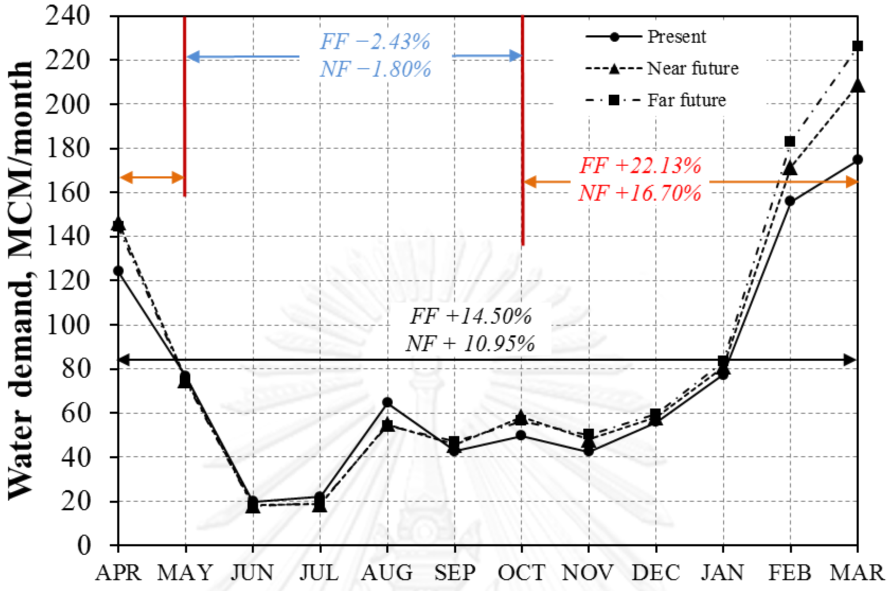
The water demand of Pitsanulok Irrigation Project was assessed on the changes by comparing the future water demand with the present water demand, as shown in Table 7-3 and Figure 7-8(a). In the near future, the water demand in the wet season will not change significantly (-1.80); however, a higher water demand will occur in October (+17.15%). On the other hand, the water demand in the dry season will increase by 16.7% and a higher water demand will occur in March (+19.48%) (as show in Figure 7-8(e)). In far future, the water demand in wet season will not change significantly (-2.43); however, a higher water demand will occur in October (+13.39%), while the water demand in the dry season will increase by 22.13% and a higher water demand will obtain in March (+29.42%). The annual water demand in the near and far future will increase by 10.95% and 14.50% compared with the present period, respectively.

Regarding the water demand of the Chao Phraya Irrigation Project is assessed, in the near future, the water demand in the wet season will not increase by 13.92%; and a greater water demand will occur in May (+52.85%). On the other hand, the water demand in dry season will increase by 27.23% and a higher water demand will occur in March (+54.7%) (as shown in Figure 7.8(b)). In the far future, the water demand in the wet season will not change significantly and a greater water demand will occur in May (+52%). On the other hand, the water demand in dry season will increase by 34% and a higher water demand will occur in March (+60.48%). The annual water demand in the near and far future will increase by 19.53% and 14.28% compared with the present period, respectively.

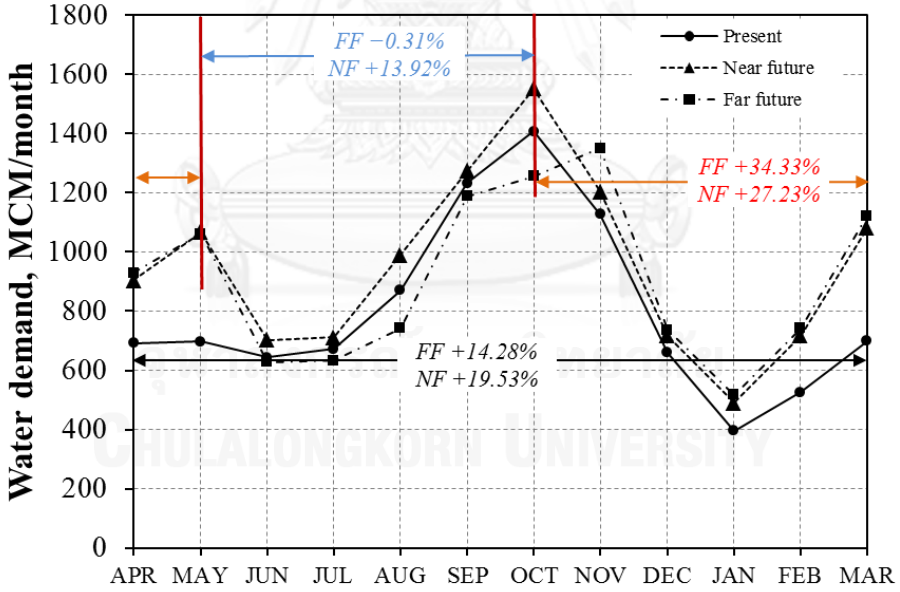
From Figure 7.8, it can be seen that regarding the comparison of water demand among the different reservoir operation, the ANFIS* will cause a greater water demand for PSK and CHY compared with the other reservoir operations. Due to this ANFIS* reservoir operation will cause the storage at the end of the season higher than the other reservoir operation, that induce a water demand decision making module providing more crop cultivation area.

Table 7.3 Summary of the irrigation water demand under the bias GCM hydrological variables

Reservoir operation	Irrigation Project	Variable	Present			Near future			Far future		
			Wet	Dry	Annual	Wet	Dry	Annual	Wet	Dry	Annual
ANFIS*	PSK	Crop requirement area (rais)	657	640	1297	659	658	1317	654	665	1319
		Water demand (MCM)	276	611	887	271	713	984	269	747	1015
		Change (%)	-	-	-	-1.80	16.70	10.95	-2.43	22.13	14.50
	CHY	Crop requirement area (rais)	4604	2856	7460	4693	3672	8365	4696	3729	8425
		Water demand (MCM)	5523	4018	9541	6292	5112	11404	5506	5397	10903
		Change (%)	-	-	-	13.92	27.23	19.53	-0.31	34.33	14.28



(a) ANFIS* – PSK



(b) ANFIS* – CHY

Figure 7.8 The comparison of water demand of ANFIS* reservoir operation

7.7.3.2 Reservoir water balance

In order to have a clear view of the adaptive reservoir under the future climate conditions, a comparison of the impact on the reservoir water balance between the ANFIS* and existing reservoir operation as used to evaluate the effectiveness under different reservoir operations, as shown in Table 7.4 and Figure 7.9.

In the near future period, the storage of the ANFIS* reservoir operation in the wet season will not change significantly (4.63%), while in the dry season it will increase 5.52% compared with the present period. In the far future, the storage of the ANFIS* reservoir operations in the wet and dry season will increase 15.48% and 13.80% compared with the present period. The annual storage in the near and far future will increase 5.18% and 11% respectively. The water balance analysis showed that the annual and seasonal storage under the ANFIS* reservoir operation rule will be located between the annual and seasonal storage under the general and flood reservoir operation rule.

In the near future period, the release of the ANFIS* reservoir operation in the wet and dry season will increase 5.89% and 7.34% compared with the present period. For the far future period, the release of the ANFIS* reservoir operation in the wet and dry season will increase 15.48% and 13.8% compared with the present period. The annual release in the near and far future will increase 6.73% and 14.5% respectively.

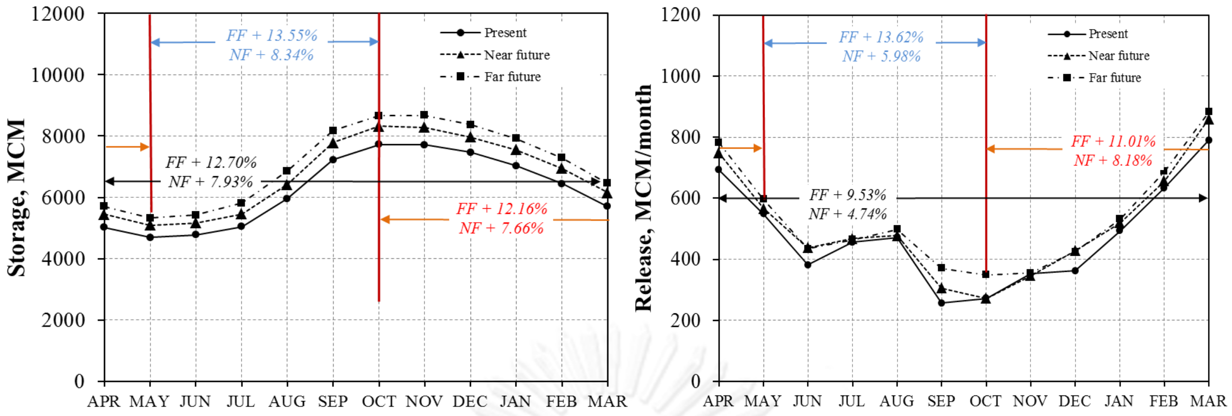
Moreover the results revealed that the ANFIS* reservoir operation will release water to a greater extent than the general and flood dam operations in both the wet and dry seasons. A comparison of the average ratio between the wet and dry release of the three cases shows that the ANFIS* case is about 0.42:0.58, the same as the general case, while the flood case is about 0.44:0.56.

The results imply that the case of ANFIS* reservoir operation will store more water in the wet season to prepare more water in the dry season, and it will release more water in the dry season in order to keep more space to allow for storing more water in the wet season, which combines the general rule and flood.

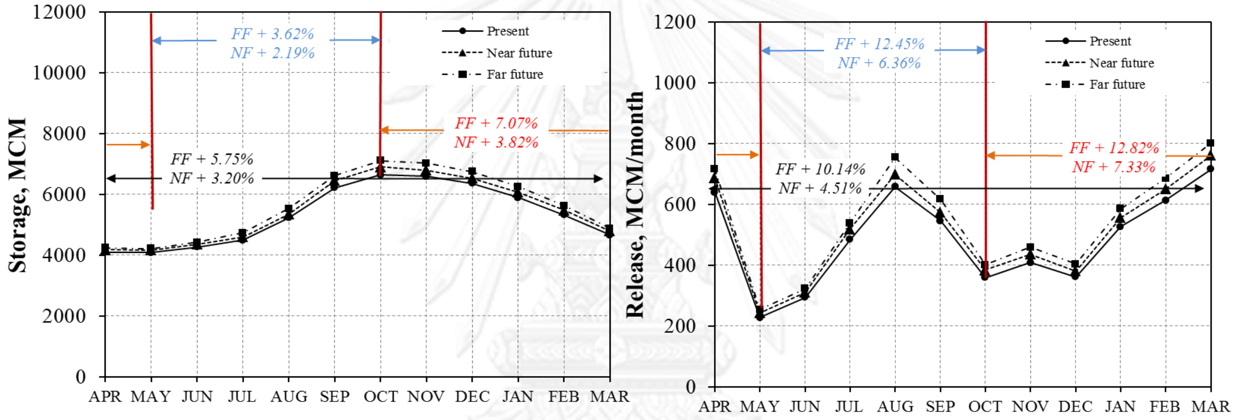
The probability of annual release by general, flood, ANFIS* reservoir operations is shown in Figure 7.10 and it was found that the probability of annual release ANFIS* will be higher compared with general reservoir operation but it still is lower than the flood reservoir operation.

Table 7.4 Summary of the reservoir operation under the bias corrected GCM hydrological variables

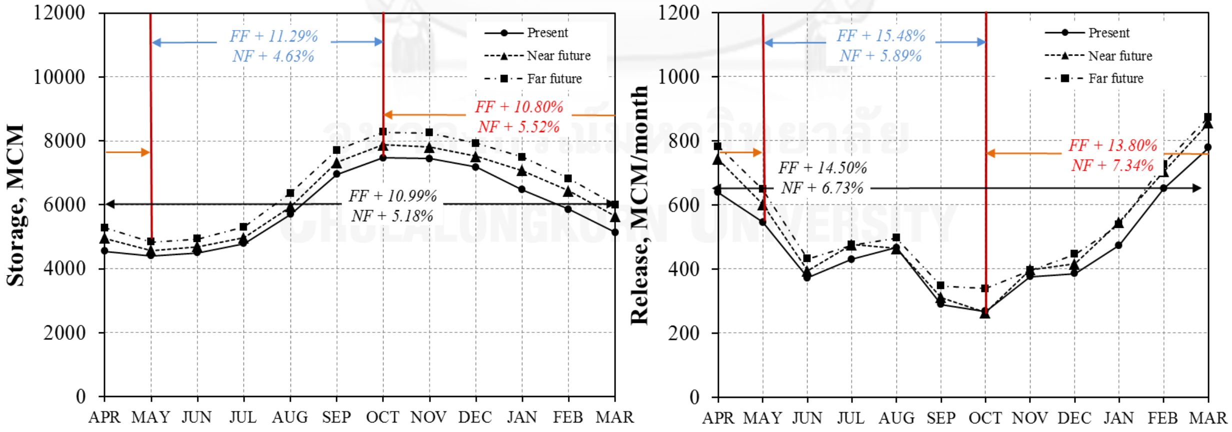
Reservoir operation	Variable	Present			Near future			Far future		
		Wet	Dry	Annual	Wet	Dry	Annual	Wet	Dry	Annual
General	Inflow (MCM)	5,189	839	6,028	5,523	845	6,369	5,845	903	6,748
	Change (%)	-	-	-	6.44	0.74	5.64	12.64	7.56	11.93
	Storage (MCM)	5,026	7,724	6,375	5,445	8,316	6,881	5,707	8,664	7,185
	Change (%)	-	-	-	8.34	7.66	7.93	13.55	12.16	12.70
	Release (MCM)	2,389	3,299	5,688	2,531	3,569	5,958	2,714	3,663	6,230
	Change (%)	-	-	-	5.98	8.18	4.74	13.62	11.01	9.53
Flood	Inflow (MCM)	5,189	839	6,028	5,523	845	6,369	5,845	903	6,748
	Change (%)	-	-	-	6.44	0.74	5.64	12.64	7.56	11.93
	Storage (MCM)	4,096	6,642	5,369	4,185	6,896	5,541	4,244	7,112	5,678
	Change (%)	-	-	-	2.19	3.82	3.20	3.62	7.07	5.75
	Release (MCM)	2,568	3,233	5,801	2,731	3,470	6,062	2,887	3,648	6,389
	Change (%)	-	-	-	6.36	7.33	4.51	12.45	12.82	10.14
ANFIS*	Inflow (MCM)	5,189	839	6,028	5,523	845	6,369	5,845	903	6,748
	Change (%)	-	-	-	6.44	0.74	5.64	12.64	7.56	11.93
	Storage (MCM)	4,718	7,469	6,093	4,936	7,881	6,409	5,250	8,275	6,763
	Change (%)	-	-	-	4.63	5.52	5.18	11.29	10.80	10.99
	Release (MCM)	2,370	3,303	5,673	2,509	3,545	6,055	2,737	3,759	6,495
	Change (%)	-	-	-	5.89	7.34	6.73	15.48	13.80	14.50



(a) General – storage (b) General – release

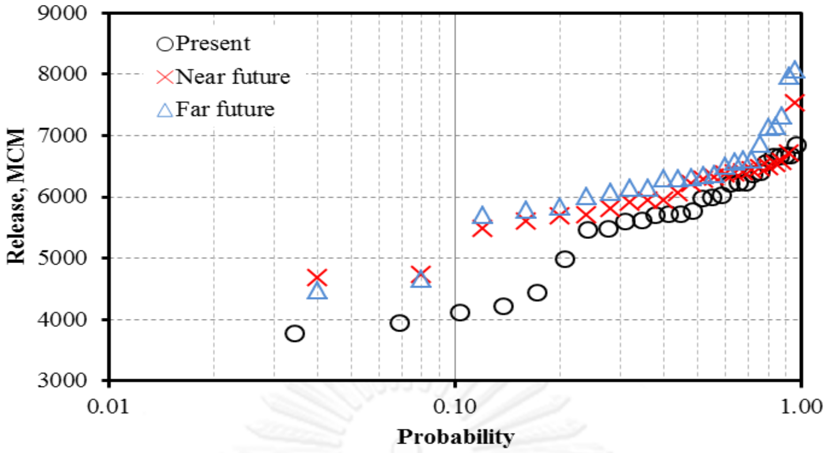


(c) Flood – storage (d) Flood – release

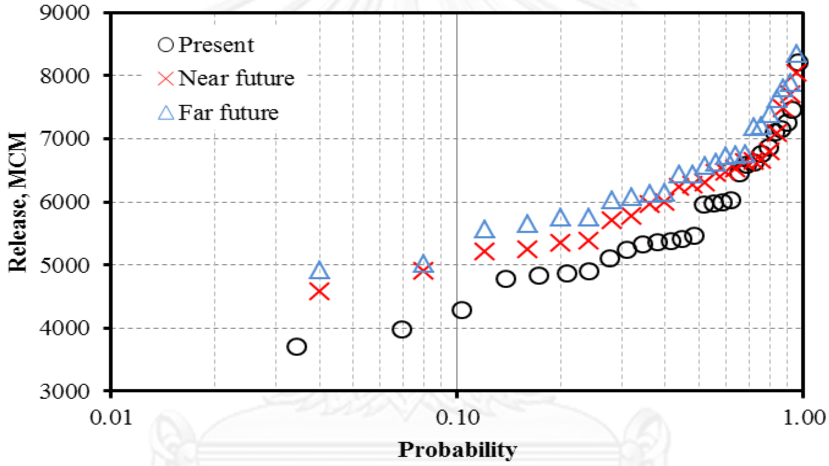


(e) ANFIS* – storage (f) ANFIS* – release

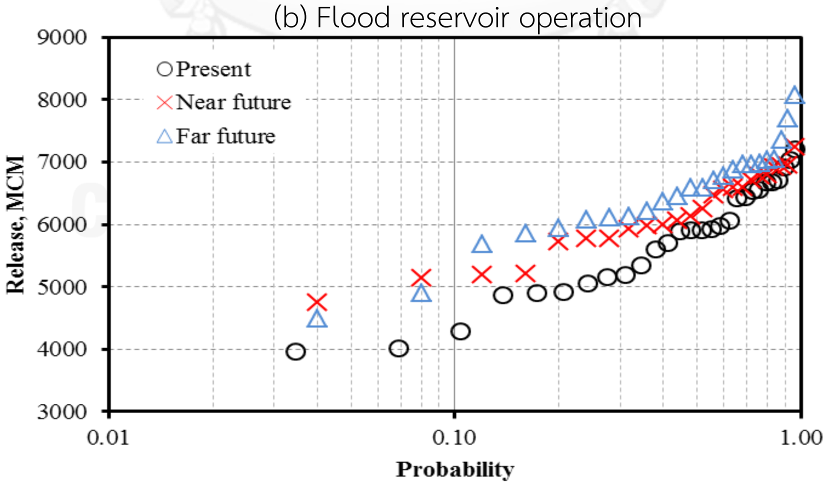
Figure 7.9 Storage and release of general, flood, ANFIS* reservoir operation under the bias GCM hydrological variables



(a) General reservoir operation



(b) Flood reservoir operation



(c) ANFIS* reservoir operation

Figure 7.10 Probability of annual release by general, flood, ANFIS* reservoir operation under the bias GCM hydrological variables

7.7.3.3 Spillage

The impact on water spillage was used to evaluate the water overflow through the spillway. The summary of average and maximum spillage is shown in Table 7.5. From the results, it was found that the maximum spillage of the ANFIS* reservoir operation in the far future will increase by 1092%; however, the spillage in the far future will occur only in 2 years. Due to the extreme inflow phenomena occur in the far future that causes water to overflow through the spillway.

Table 7.5 Summary of the maximum spillage by general, flood and ANFIS* reservoir operation

Reservoir operation	Spillage	Actual	Present	Near future	Far future
General	Average (MCM)	393.4	19.8	422.3	205.1
	Maximum (MCM)	1164.8	409.3	422.3	484.9
	Change (%)	-	-	3.18	18.47
	Number of spillage (years)	7	3	3	7
Flood	Average (MCM)	393.4	114.2	-	-
	Maximum (MCM)	1164.8	114.2	-	-
	Change (%)	-	-	-	-
	Number of spillage (years)	7	1	-	-
ANFIS*	Average (MCM)	393.4	3	-	53.8
	Maximum (MCM)	1164.8	84	-	1092.6
	Change (%)	-	-	-	1200.7
	Number of spillage (years)	7	1	-	2

7.6.2.4 Water shortage

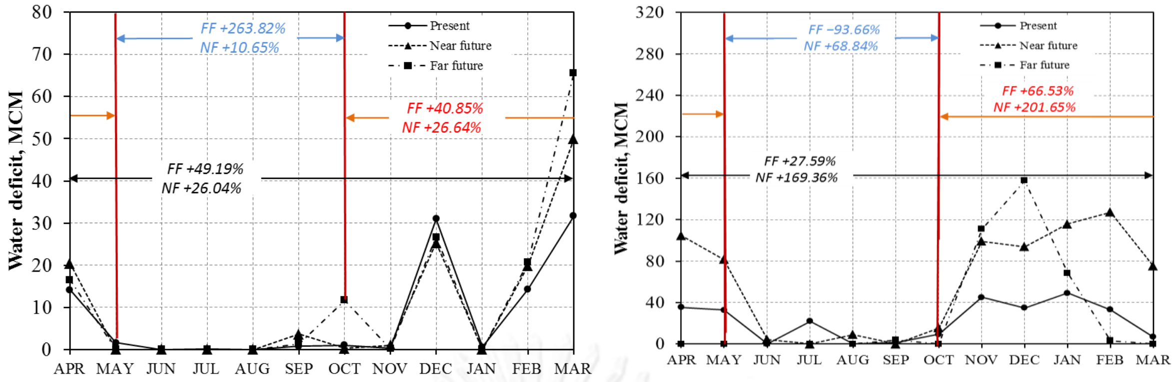
The water deficit of the Pitsanulok Irrigation Project by ANFIS* could be assessed on the impact by comparing the future water deficit per demand with present water deficit per demand. In near future, the water deficit per demand in wet season will decrease (-3.72%) and a higher water deficit per demand will occur in June. The water deficit in the dry season will not change significantly (-0.10%) and a higher water deficit per demand will occur in December (shown in Figure 7-12(e)). The annual water deficit per demand will decrease by -1.91%. In the far future, the water deficit per demand in the wet season will decrease (-5.74%); and less water deficit per demand will tend to decrease will occur in May by -9.08%. The water deficit in the dry season will decrease not significantly by -0.41%, especially from November to February (as shown in Figure 7-12(e)). For the water deficit of the Chao Phraya Irrigation Project, in near future, the water deficit per demand in wet season will increase not significantly (+0.36%) and a higher water deficit per demand will occur in May. The water deficit in the dry season will increase by 5.19% and a higher water deficit per demand will occur in December (shown in Figure 7-12(f)). The annual water deficit per demand will decrease by 2.78%. In the far future, the water deficit per demand in the wet season will increase not significantly (+0.76%); and more water deficit per demand will tend to decrease will occur in September by 7.73%. The water deficit in the dry season will increase by 4.40%, especially from November to January (as shown in Figure 7-12(f)).

From the comparison of the annual water deficit between the ANFIS* and existing reservoir operations, it was found that the developed ANFIS* reservoir operations can reduce a water deficit better than the general dam operation. However, the water deficit per demand of the ANFIS* is closer to general reservoir operation, and in contrast it is higher than flood reservoir operation. However, the water demand of the ANFIS* is higher than both of reservoir operations; that means that the ANFIS* can provide a greater crop cultivation area. Furthermore, the ANFIS* can reduce the maximum water deficit better than the other reservoir operations. Although the flood reservoir operation can cause a greater water deficit per demand, it will cause fewer crop cultivation area. From the results can conclude the ANFIS* will be more efficient in managing the release to the irrigated area.

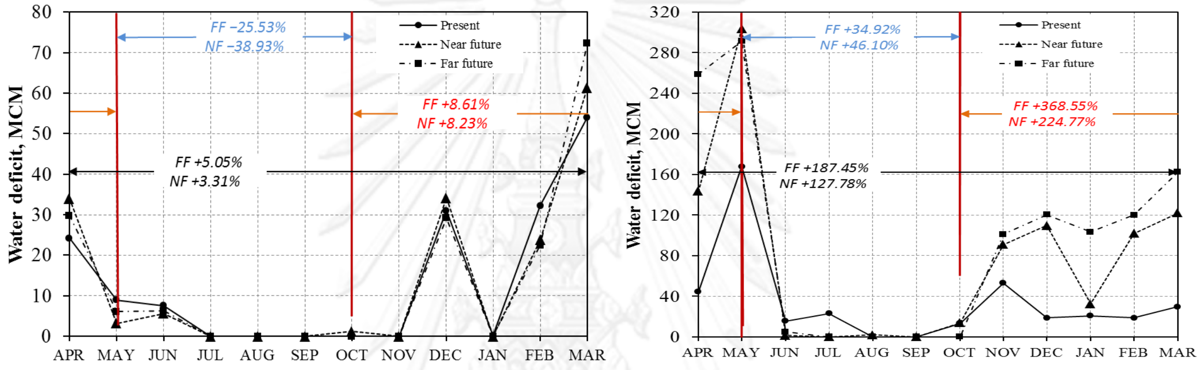
The evaluation of the extreme shortage events according to the ANFIS* dam operation was considered to be the same as general and flood dam operations. The moderate and extreme shortage of this operation is summarized in Table 7.7. The monthly water deficit per demand according to the ANFIS* dam operation is shown is shown in Figure 7.13. From the results, it was found that the ANFIS* dam operation can reduce the water deficit more efficiently than the other dam operations.

Table 7.6 Summary of the water shortage under ANFIS* reservoir operation

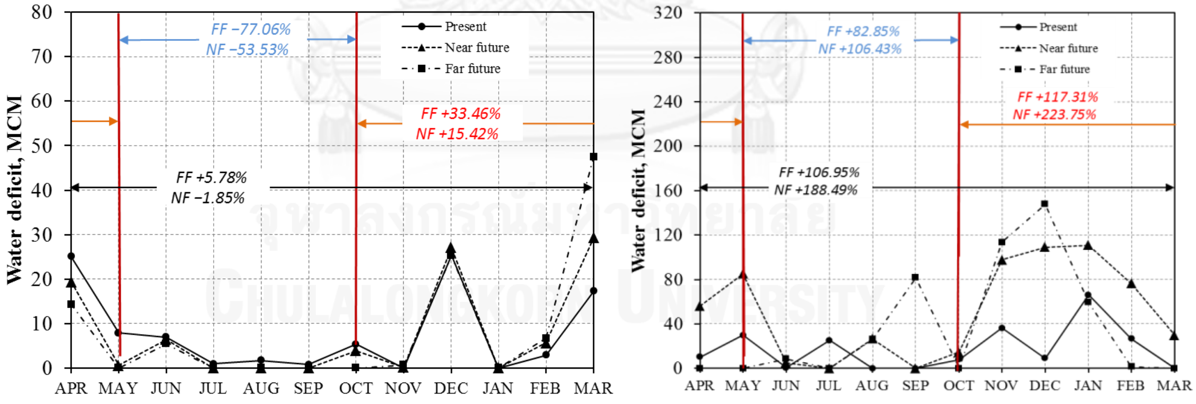
Irrigation Project	Statistics	Present (28 years)			Near future (25 years)			Far future (25 years)		
		Wet	Dry	Annual	Wet	Dry	Annual	Wet	Dry	Annual
Phitsanulok	Mean (MCM)	24	71	94	11	82	93	5	94	100
	Maximum (MCM)	110	241	288	65	294	299	18	185	189
	Average percentage of water deficit per water demand (%)	10.34	13.07	11.71	6.63	12.97	9.80	4.61	12.66	8.63
	Maximum percentage of water deficit per water demand (%)	50.54	34.06	35.10	23.24	39.32	22.33	11.75	21.35	14.08
	Number of water shortage (years)	27	24	27	22	23	23	20	23	23
	Frequency (times/season,times/year)	0.33	0.38	0.33	0.20	0.41	0.30	0.17	0.44	0.29
	Maximum of continuous water shortage year (years)	-	-	28	-	-	24	-	-	24
Chao Phraya	Mean (MCM)	66	150	216	131	480	611	116	322	439
	Maximum (MCM)	432	1064	1,374	638	2,346	2,638	1074	1258	1,258
	Average percentage of water deficit per water demand (%)	1.13	4.06	2.59	1.49	9.38	5.43	1.89	8.59	5.24
	Maximum percentage of water deficit per water demand (%)	8.15	38.71	21.88	7.25	38.81	20.88	19.71	23.50	12.56
	Number of water shortage (years)	6	11	12	9	17	20	6	19	19
	Frequency (times/season,times/year)	0.22	0.33	0.21	0.19	0.39	0.21	0.19	0.23	0.14
	Maximum of continuous water shortage year (years)	-	-	4	-	-	13	-	-	10



(a) General – Phitsanulok Project (b) General – Chao Phraya Project

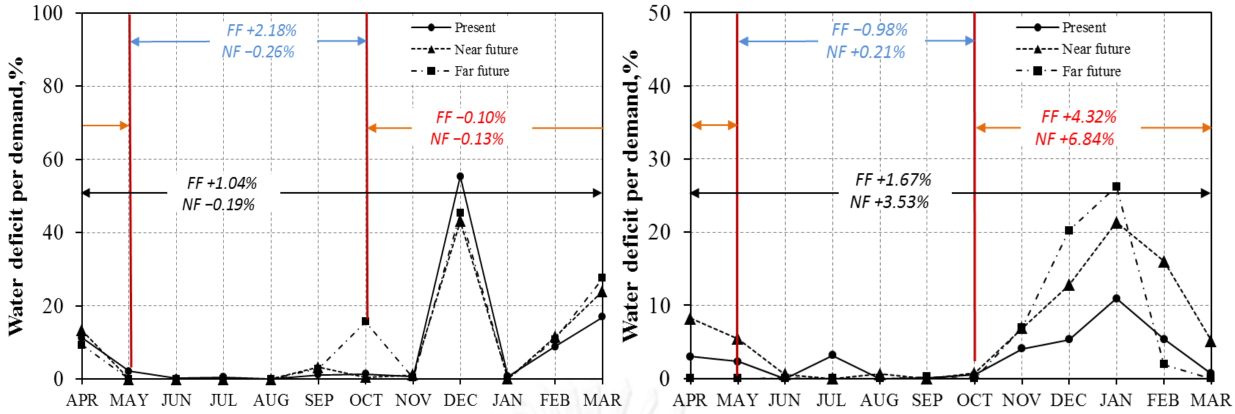


(c) Flood – Phitsanulok Project (d) Flood – Chao Phraya Project

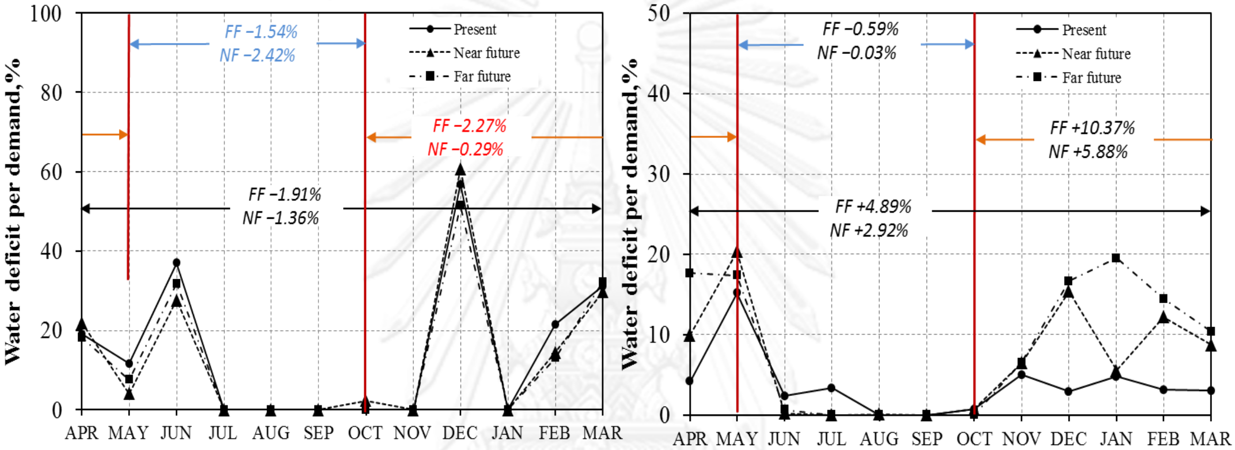


(e) ANFIS* – Phitsanulok Project (f) ANFIS* – Chao Phraya Project

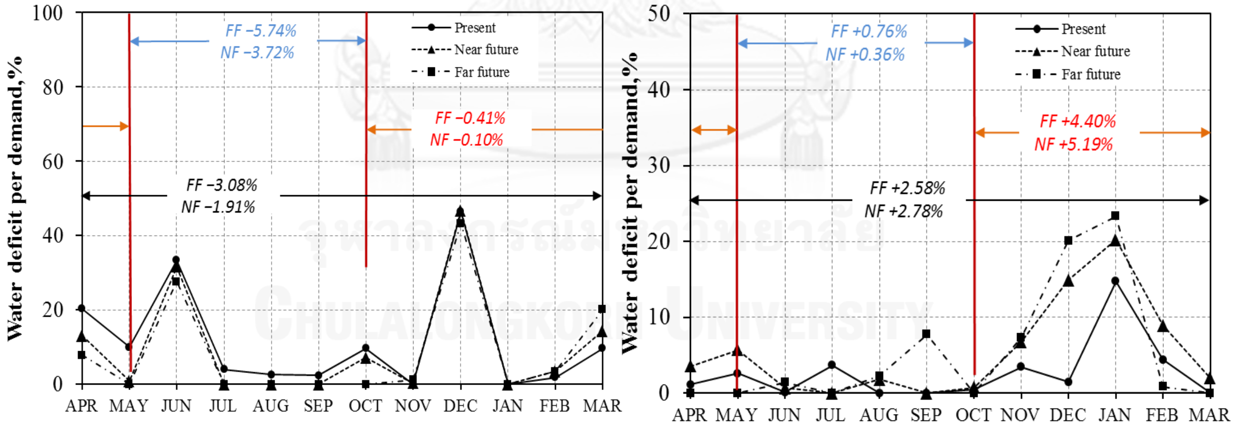
Figure 7.11 Water deficit of Phitsanulok and Chao Phraya Irrigation Project by general, flood and ANFIS* reservoir operation



(a) General – Phitsanulok Project (b) General – Chao Phraya Project



(c) Flood – Phitsanulok Project (d) Flood – Chao Phraya Project

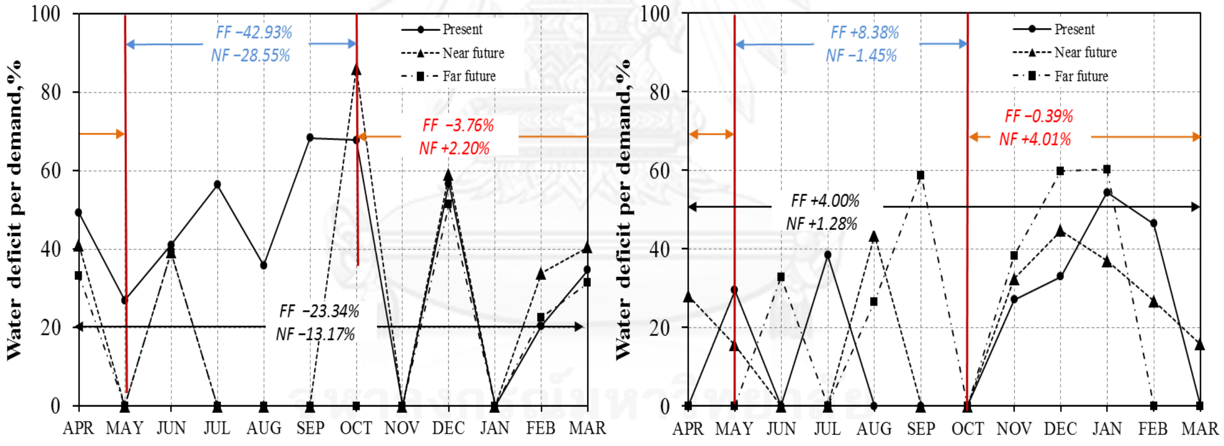


(e) ANFIS* – Phitsanulok Project (f) ANFIS* – Chao Phraya Project

Figure 7.12 Water deficit per demand by general, flood and ANFIS* reservoir operation

Table 7.7 Summary the extreme shortage by ANFIS* dam operation

Project	Statistics	Present (28 years)			Near future (25 years)			Far future (25 years)		
		Wet	Dry	Annual	Wet	Dry	Annual	Wet	Dry	Annual
PSK	Mean (MCM)	127	186	313	57	237	294	8	214	222
	Average percentage of water deficit per water demand (%)	49.45	26.88	38.16	20.90	29.08	24.99	6.52	23.12	14.82
	Number of water shortage (years)	6	11	20	2	6	18	0	12	17
CHY	Mean (MCM)	637	983	1620	862	1917	2779	1109	1199	2308
	Average percentage of water deficit per water demand (%)	11.30	26.79	19.04	9.85	30.80	20.32	19.68	26.40	23.04
	Number of water shortage (years)	0	2	5	0	8	8	1	5	8



(a) Phitsanulok Irrigation Project (b) Chao Phraya Irrigation Project

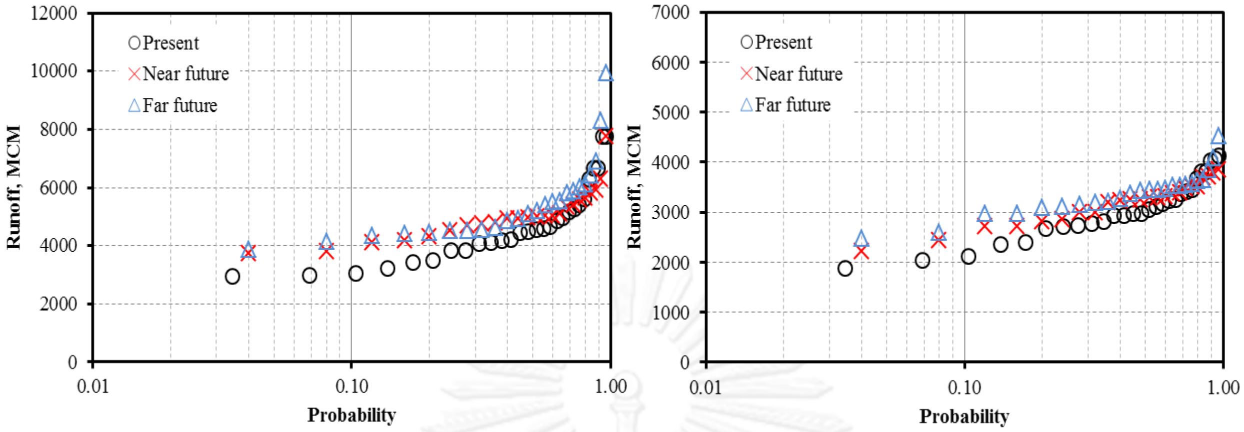
Figure 7.13 Water deficit per demand of Phitsanulok and Chao Phraya Irrigation Project under ANFIS* dam operation in extreme shortage case

7.7.3.5 Seasonal runoff and accumulative runoff

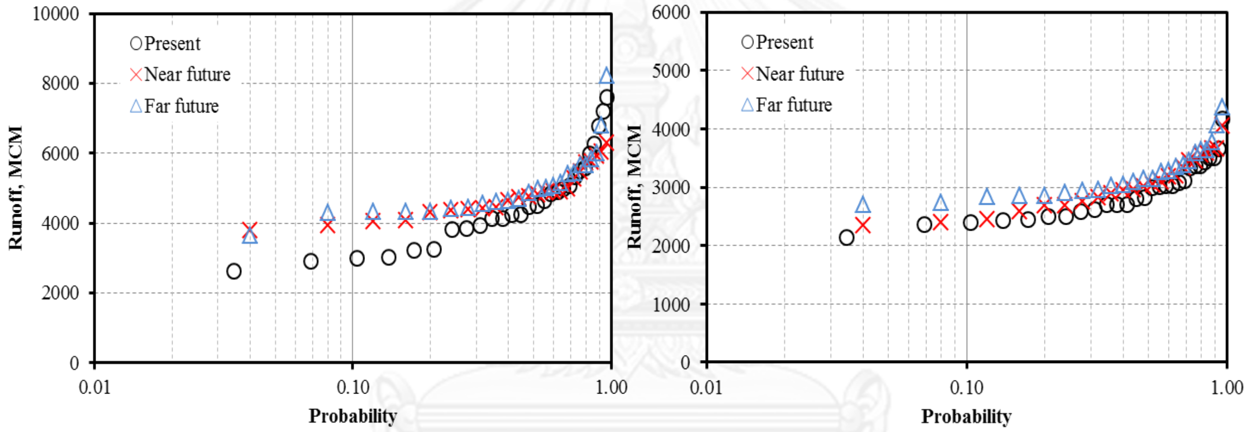
The seasonal runoff at the runoff stations along the main Nan River was assessed the impact of the reservoir operations. A summary of the seasonal runoff according to general, flood and ANFIS* is shown in Table 7.8. In the near future, the seasonal runoff of the ANFIS* in the wet and dry season will increase 5% - 13% and 8% - 19%, respectively. The annual runoff will increase 8% - 15%. In the far future, the seasonal runoff of the ANFIS* in the wet and dry season will increase 14% - 23% and 15% - 26%, respectively. The annual runoff will increase 15% - 24%. From the result was found that the ANFIS* will cause a higher runoff along the main Nan River Basin. The probability of seasonal runoff of the ANFIS* of N.5A and C.2 will tend to increase compared with the other reservoir operations as shown in Figure 7.14 and 7.15. Due to the ANFIS* reservoir operation will be released more water in both wet and dry season.

Table 7.8 Summary of the seasonal and annual runoff by general, flood and ANFIS* reservoir operation

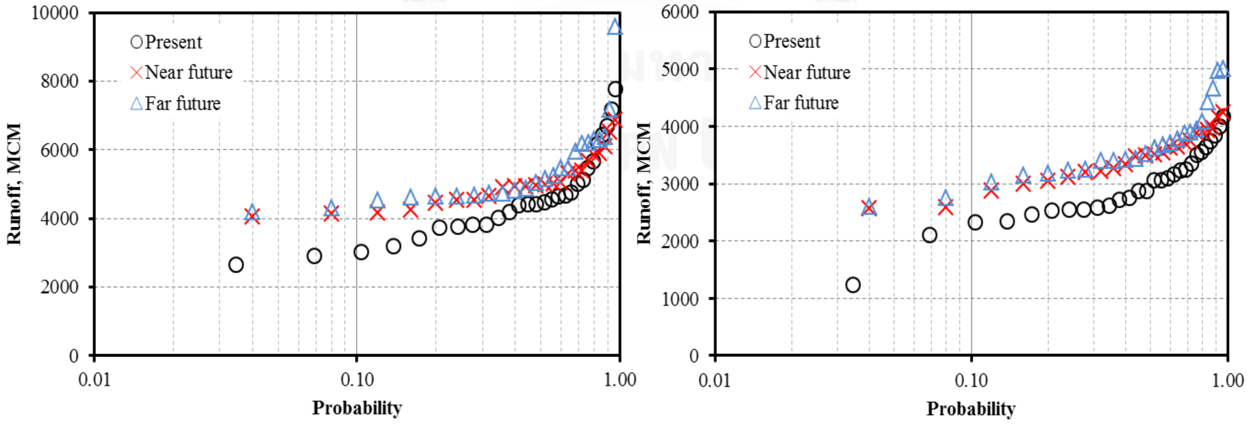
Dam operation	Control point	Present			Change in near future (%)			Change in far future (%)		
		Wet	Dry	Annual	Wet	Dry	Annual	Wet	Dry	Annual
General	N.12A	2,869	3,607	6,475	6.00	3.22	4.45	14.43	9.42	11.64
	N.60	3,938	4,164	8,102	5.48	2.98	4.20	12.74	9.83	11.24
	N.27A	3,075	2,651	5,725	8.20	1.71	5.19	19.55	10.18	15.21
	N.5A	4,729	3,067	7,797	7.18	1.07	4.78	16.17	10.21	13.82
	N.7A	6,754	3,881	10,635	7.43	0.78	5.00	13.59	10.17	12.34
	N.67	9,520	4,859	14,379	9.68	1.24	6.83	15.83	10.33	13.97
	C.2	13,984	8,965	22,949	9.23	2.57	6.63	17.04	14.21	15.94
Flood	N.12A	3,149	3,585	6,734	1.97	4.27	3.20	7.47	9.66	8.64
	N.60	4,249	4,210	8,459	1.76	2.67	2.21	6.87	8.29	7.58
	N.27A	3,072	2,611	5,683	1.62	1.53	1.58	8.94	6.38	7.77
	N.5A	4,695	3,046	7,742	3.20	0.89	2.29	9.57	6.72	8.45
	N.7A	6,860	3,854	10,713	1.43	-0.76	0.65	6.10	5.32	5.82
	N.67	10,564	4,878	15,443	6.92	-0.69	4.52	8.72	5.28	7.64
	C.2	15,534	9,488	25,022	4.83	0.19	3.07	6.12	7.53	6.66
ANFIS*	N.12A	2,840	3,558	6,398	5.33	10.89	8.42	15.85	14.82	15.28
	N.60	3,909	4,087	7,996	4.96	10.83	7.96	14.08	15.31	14.71
	N.27A	3,010	2,561	5,571	11.62	19.31	15.16	23.06	25.81	24.32
	N.5A	4,660	2,970	7,630	9.21	16.35	11.99	18.10	23.48	20.19
	N.7A	6,661	3,739	10,400	8.66	14.13	10.63	15.07	21.62	17.42
	N.67	9,493	4,734	14,227	12.91	10.72	12.18	16.75	18.18	17.23
	C.2	14,028	8,911	22,939	11.16	7.70	9.82	15.70	17.37	16.35



(a) General – wet season (b) General – dry season

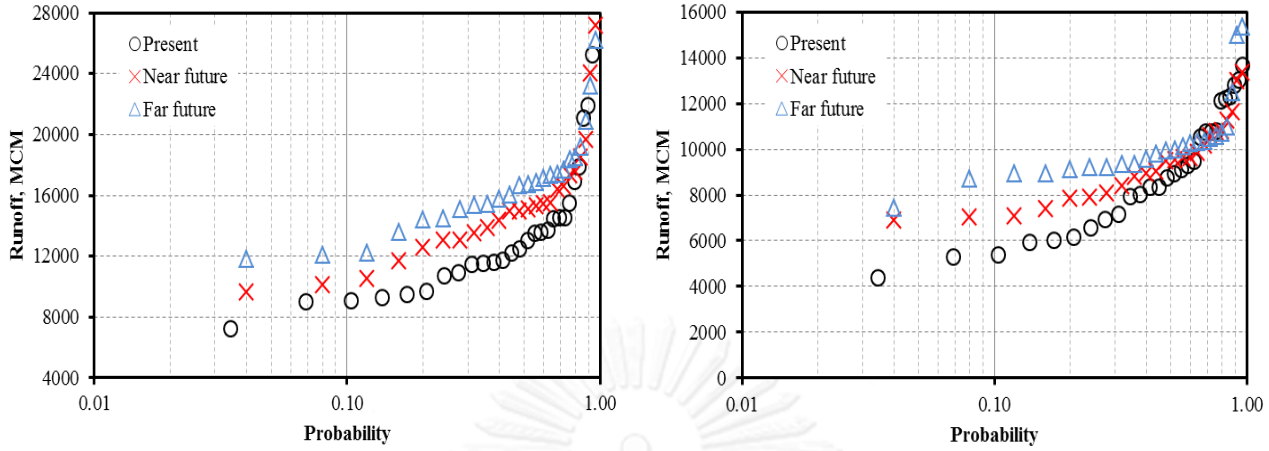


(c) Flood – wet season (d) Flood – dry season

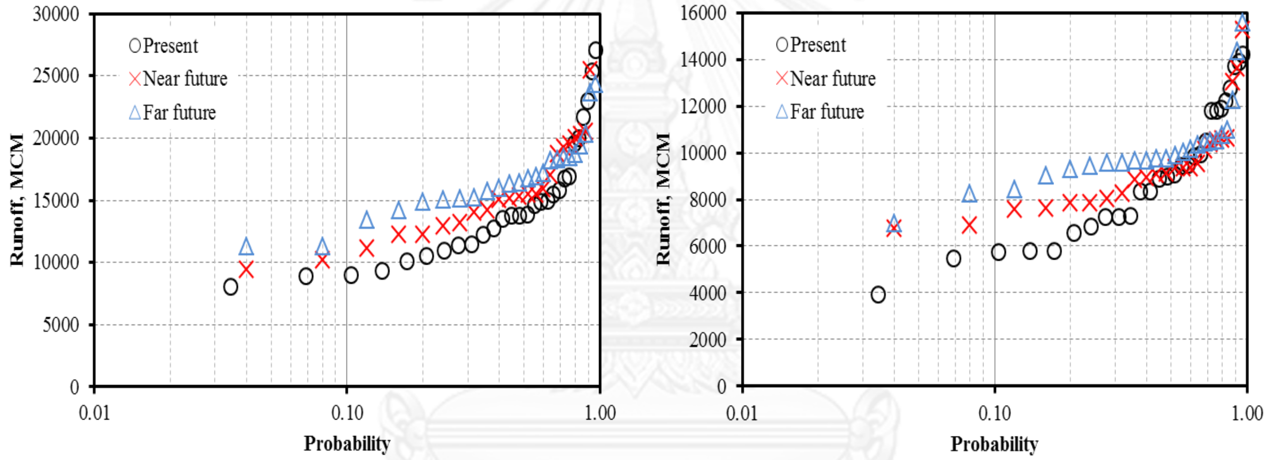


(e) ANFIS* – wet season (f) ANFIS* – dry season

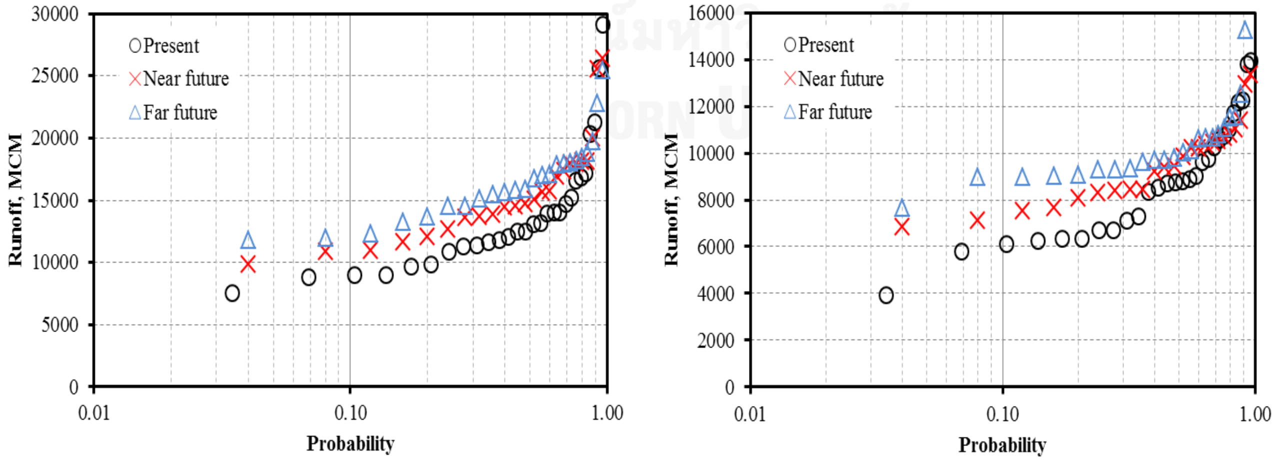
Figure 7.14 Probability of seasonal runoff of N.5A by general, flood, ANFIS* reservoir operation



(a) General – wet season (b) General – dry season



(c) Flood – wet season (d) Flood – dry season



(e) ANFIS* – wet season (f) ANFIS* – dry season

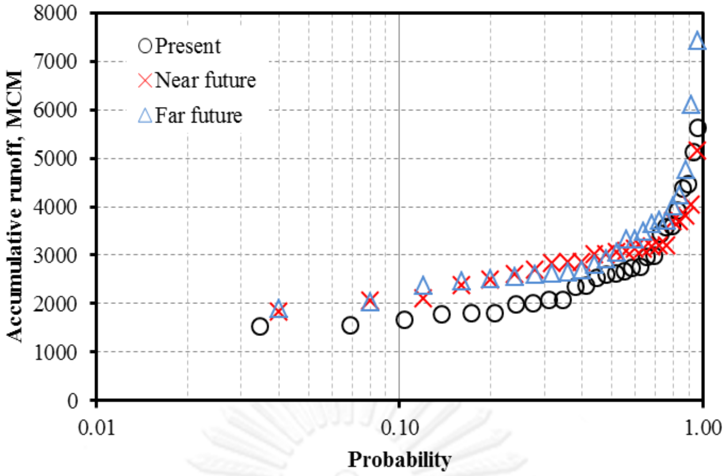
Figure 7.15 Probability of seasonal runoff of C.2 by general, flood, ANFIS* reservoir operation

The comparison of maximum accumulative runoff (August to October) among general, flood and ANFIS* reservoir operation is shown in Table 7.9. The ANFIS* can reduce the maximum accumulative runoff better than the general reservoir operations; however, the flood reservoir operation still can reduce more efficiently than other reservoir operations except that the flood event at N.67 runoff station will occur more frequently than the others. Due to the higher lateral flow of Yom River Basin induce to the accumulative runoff at N.67 increase.

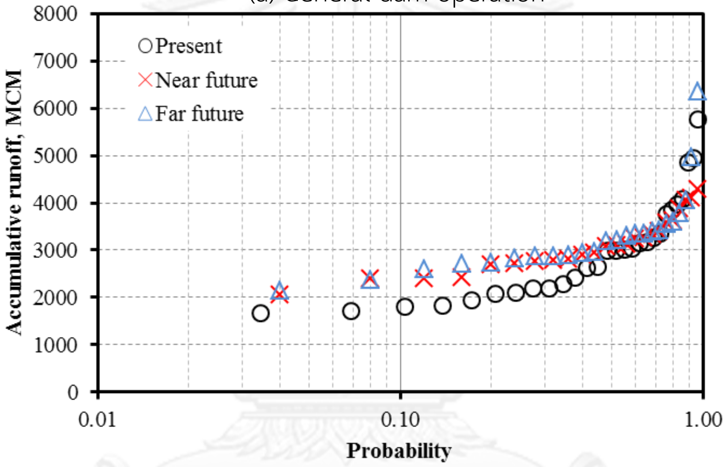
The probability of a maximum accumulative runoff at N.5A and C.2 is lower than for the others, as shown in Figure 7.16 and 7.17.

Table 7.9 Summary of the accumulative runoff by general, flood and ANFIS*, reservoir operation

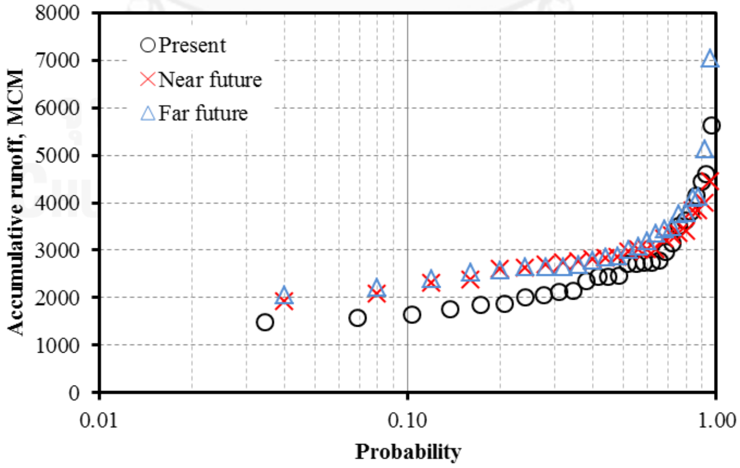
Dam operation	Control point	Maximum Capacity (MCM)	Maximum accumulative runoff in present(MCM)	Change in near future (%)	Change in far future (%)	Number of flood event (years)		
						Present	Near future	Far future
General	N.12A	2756	2263	17.63	65.62	0	0	2
	N.60	3825	3572	-7.61	49.52	0	0	2
	N.27A	2916	3291	-0.40	57.70	3	1	4
	N.5A	4804	5617	-8.47	32.10	2	1	2
	N.7A	6147	7798	-17.07	35.91	6	1	5
	N.67	7801	12649	2.20	12.70	9	7	9
	C.2	12087	21440	-1.60	-9.08	4	6	10
Flood	N.12A	2756	5046	-42.89	-37.14	2	1	3
	N.60	3825	7130	-46.87	-33.16	4	0	1
	N.27A	2916	4606	-42.23	-10.46	3	0	2
	N.5A	4804	6795	-36.95	-6.65	4	0	2
	N.7A	6147	8198	-22.37	17.27	7	3	2
	N.67	7801	16368	-18.02	-16.73	13	15	16
	C.2	12087	28560	-14.96	-30.66	9	9	10
ANFIS*	N.12A	2756	2258	-16.08	63.91	0	0	1
	N.60	3825	3567	-13.15	48.44	0	0	0
	N.27A	2916	3109	-16.21	54.78	2	0	3
	N.5A	4804	5623	-20.91	25.06	1	0	2
	N.7A	6147	7553	-12.55	36.04	6	1	4
	N.67	7801	12586	2.83	10.37	8	6	8
	C.2	12087	21259	-5.94	-10.70	4	6	9



(a) General dam operation

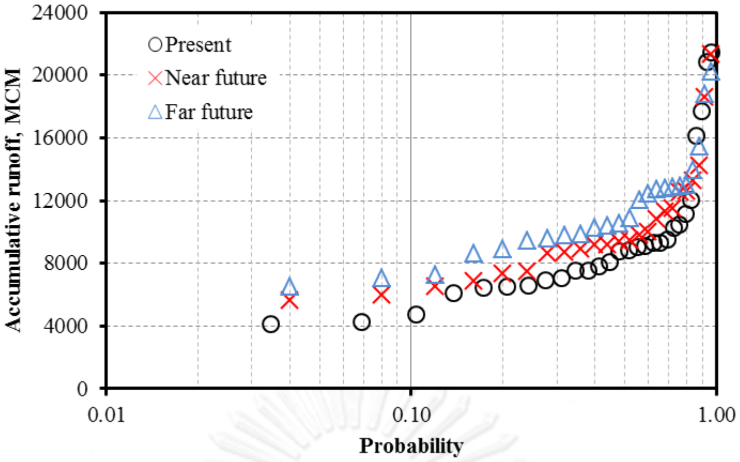


(b) Flood dam operation

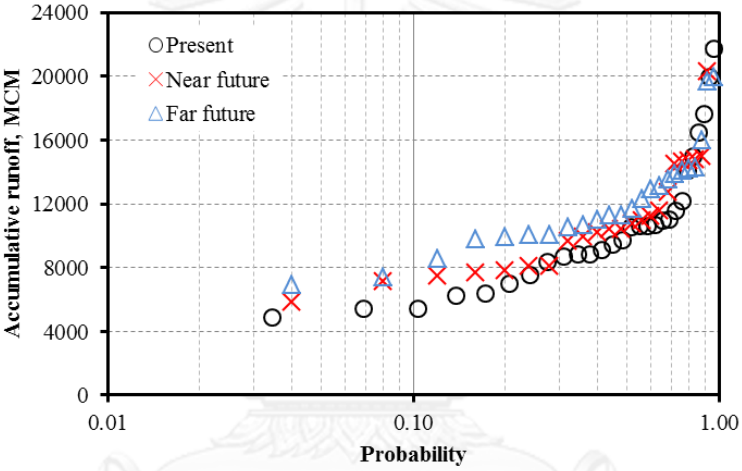


(c) ANFIS* dam operation

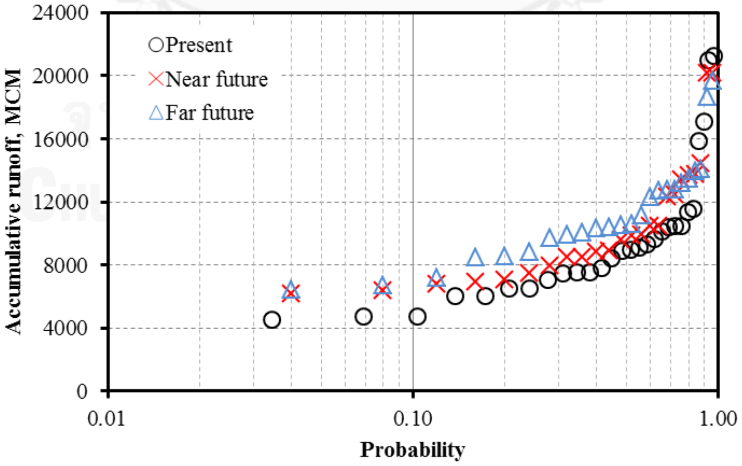
Figure 7.16 Probability of accumulative runoff of N.5A by general, flood and ANFIS* dam operation



(a) General dam operation



(b) Flood dam operation



(c) ANFIS* dam operation

Figure 7.17 Probability of accumulative runoff of C.2 by general, flood and modified ANFIS* dam operation

7.7.4 Proposed reservoir operation rule curve

From the storage results of the adaptive reservoir operation, the proposed reservoir operation could be established by using the probability of monthly storage. (plotting position method) The lower rule curve was derived from the probability at 20%, while the upper rule curve was derived from the probability at 80%. A comparison of the proposed, existing, and revised in 2012 reservoir rule curves is shown in Figure 7.18. The proposed rule curve suggests the release of more water from November to July, while Sirikit Dam should store more water from August to October.

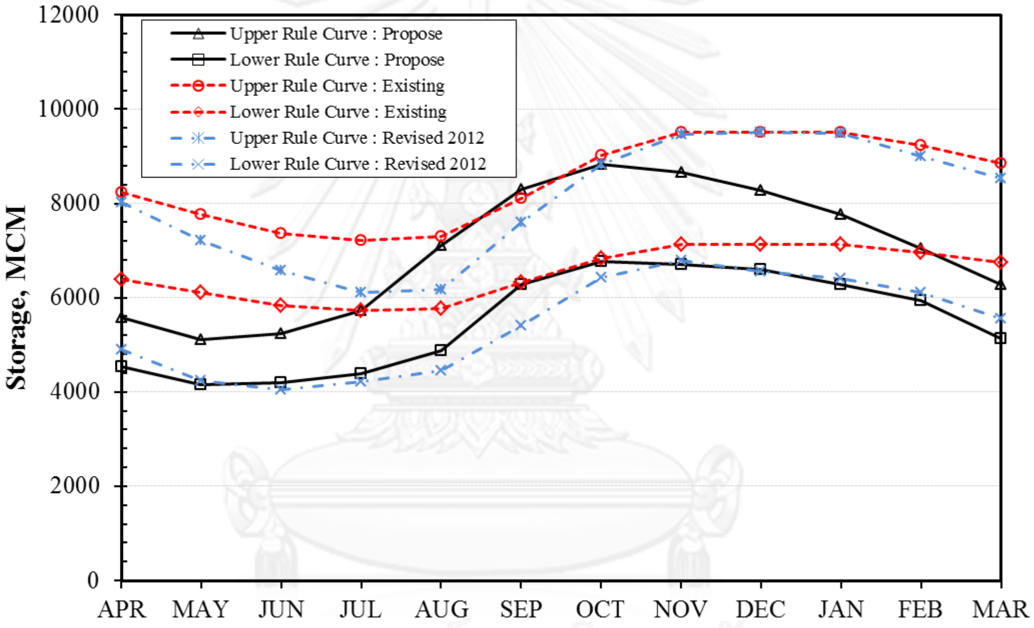


Figure 7.18 The proposed reservoir rule curves of Sirikit Dam

7.8 Actual application guides

The system is developed for the climate change impact and adaptation study based on the GCM bias corrected data. The system envisaged the variables for dam operation by using appropriate release ratio figure under the consideration of inflow, storage, water demand (through water demand decision making module), and lateral flow in the downstream area. The medium term and short term forecasting modules is needed to be applied for such data. There are many tool for the purpose e.g. the relationship between rainfall and SST Nino 3.4

(e.g. Chaowiwat and Koontanakulwong, 2012). By using this tool, the near term weather can be forecasted. However, in the real situation, dam operator will not know the future climate data.

The adaptive reservoir operation can be applied for the real situation by using the forecasting weather in the next 3 months. Regarding the input variables of reservoir operation system included the two main variables: the estimated runoff and the decision making variable. Hence, the estimated runoff can be used the HEC-HMS model to simulate the runoff by the forecasting rainfall in next 3 month. Thus, the forecasting climate in next 3 months can be found from the relationship between the climate and sea surface temperature. The decision making variables comprised two dataset: the weather dataset for water demand decision making module and the weather dataset for reservoir release function. From Figure 7.19, It can be proposed the new researching issues that it should be brought to consider. The researched issues for each component can be explained as follows.

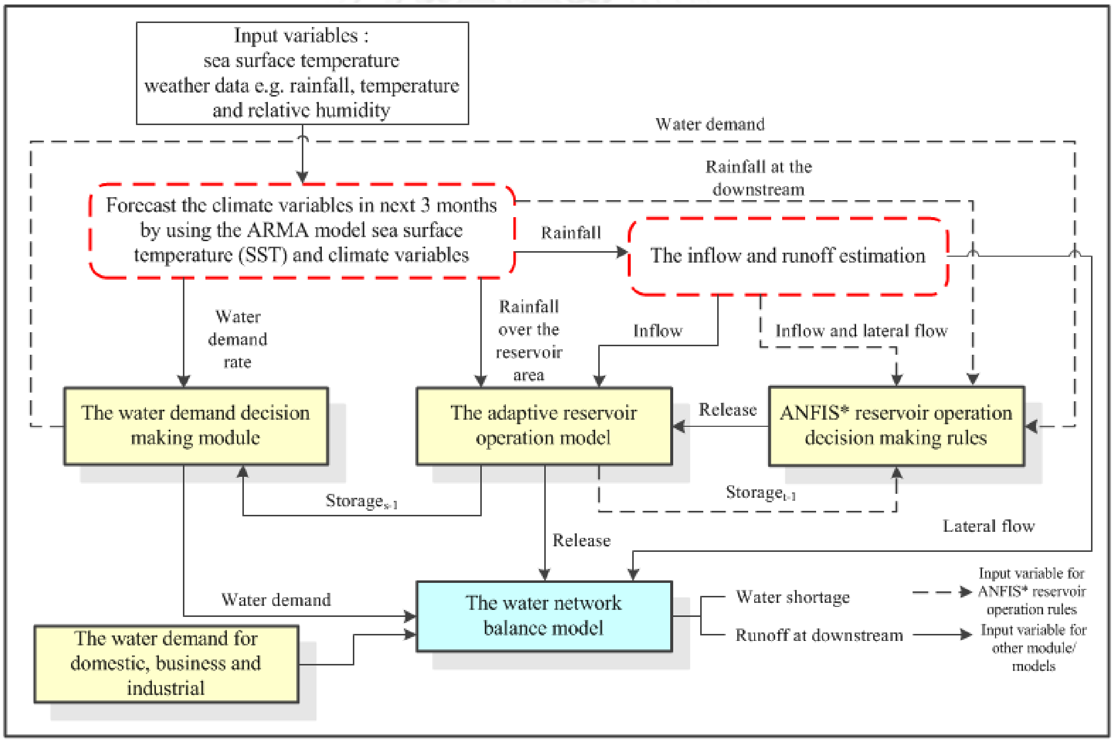


Figure 7.19 Flowchart diagram of the adaptive reservoir operation for the real situation

The water demand decision making module: The limitation of this reservoir operation system is the crop cultivation area for water demand estimation based on the historical cultivated area in Phitsanulok and Chao Phraya Irrigation Project and the storage of Sirikit and Bhumibol Dam. The concept of this decision making module was considered from the relationship of the storage and cultivated area by using probability tree classification method. However, nowadays there are many factors affect to the rice planting, the rice cropping system become more complex that cause difficult to deal with the reservoir and water management.

In the past, the farmer cultivated major and second rice more restrictively than the present due to the population and economy in the central region growth very fast. The majority of farmers in the central plain do not have their ownership on the paddy field, so they have to plant more crops per year much as possible by using the short ages of rice type. Some paddy types can be growth in 99 – 103 days e.g. Chainat80, Rachini, Pung Thong, Kao Phathum etc. (http://www.brrd.in.th/) ; normally its planting age about 110 days; so the farmers will continue planting the rice. Especially the second rice crop in the second round (2nd second rice) will tend to increase in some irrigation projects. This reason caused the farmers increase their own efficiency for searching water to subsidy the insufficient period especially the groundwater is the alternative water resources. It was found that the planting area was over than the planed area. Hence, the water demand estimation in this study was assumed the cropping pattern in roughly based on the entire of irrigation project area. In the real situation, the farmers in each project do not start to plant the paddy in the same time, it cause this model overestimating some months. Furthermore, the irrigation efficiency of each project should be concerned, due to the irrigation system of each project vary on the condition of hydraulic infrastructure and allocation system.

Furthermore, the other uncertain factors that affected to the farmers deciding to plant the 2nd second rice including the rice mortgage scheme, economy factors e.g. the rice price, the cultivated wage for planting rice process and productive cost etc. Hence, the cropping area will tend to increase continuously; it caused the water allocation insufficient to serve the water needs. The cropping pattern also is one importance issues that should be considered, due to the farmers did not follow the water allocation plan which issued by RID.

This reservoir operation system can be improved by integrating the related input variables to deal with the crop cultivation area. Therefore, the elimination of the limitation of this system is to be concerned on the water budget and the related factors together to enhance this system more reliability. The advance techniques should be adopted to forecast the crop cultivation area e.g. crop weather forecasting model with economic factors.

The water network balance model for this study was focused on the large scale irrigation projects included Phitsanulok and Chao Phraya Irrigation Projects, it can be used to study the overview for the reservoir operation only. In the practical application, the detail of individual irrigation project should be considered for the water management including the irrigated area, cropping pattern and irrigation efficiency. The return flow of this study was assumed about 20% by the amount of water allocation. In the present, the farmers tend to utilize this residual water to plant the paddy in some insufficient water allocation zone. Therefore, the return flow of the irrigation projects should be explored more details.

7.9 Summary of adaptive reservoir operation

From the results the adaptive reservoir operation can be summarized as follows:

1) The ANFIS* reservoir operation will result more water demand of the PSK and CHY irrigation projects compared with the other reservoir operations. The ANFIS* reservoir operation will affect to the storage at the end of season to be higher than the other reservoir operations, that cause the water demand decision making module to determine more crop cultivation area.

2) The annual and seasonal storage under the ANFIS* reservoir operation rule will be between the annual and seasonal storage under the general and flood reservoir operation rule. The ANFIS* reservoir operation will store more water in the wet season to prepare for more water in the dry season,

and it will release more water in the dry season in order to keep more space to allow for storing more water in the wet season that combine the general rule and flood together.

3) The ANFIS* reservoir operation can reduce the spillage in the general case in the present and in the near future but spillage will still occur in the extreme inflow case.

4) The ANFIS* reservoir operation can reduce the water deficit better than the general dam operation, and it can reduce the maximum water deficit better than the other reservoir operations. Although the flood reservoir operation can reduce the water deficit per demand, it will cause fewer crop cultivation area.

5) The ANFIS* reservoir operation releases more water in both the wet and dry season, and that causes higher seasonal runoff at the downstream runoff stations.

6) The ANFIS* reservoir operation can reduce the maximum accumulative runoff better than the general reservoir operation; however, the flood reservoir operation still can reduce more efficiently than the other reservoir operations.

CHAPTER VIII
CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

1) The performances of different GCMs were compared by using the goodness of fit tests, and it was found that the MRI-A1B GCM precipitation gives best performances compared with the other GCMs in this study (see Table 4.1). Because MRI-GCM grid size is the higher resolution. Regarding the GCM model which provided the higher mean precipitation can be used to study the flood situation. Other another hand, the lower mean precipitation can be used to study the drought or the water management. Furthermore, the GCM models which give higher temperature and relative humidity can be used to apply for study for the water demand.

2) The four bias correction methods used for comparison study here included the Gamma-Gamma transformation, the SD ratio, the Hybrid method, and the modified rescale method. They were compared to select a suitable bias correction for the catchment scale climate change impact assessment. The SD ratio and the Hybrid-GCM method provide a probability distribution pattern for rainfall closer to the observed pattern, except for lower and higher rainfall intensity. The hybrid method reduces the biases as well in the high intensity rainfall in the rainy season, while the SD ratio method is able to reduce biases as well in the low intensity rainfall in the dry season. The monthly mean rainfall distribution pattern in the rainy season, the SD Ratio-GCM, and the Hybrid-GCM values were found to be close to the average observed rainfall, with less residual range variation. The hybrid bias correction method was found to be the relatively best bias correction, as it gives better correlation with respect to monthly rainfall amount in terms of the temporal and spatial distributions.

3) The evaluation of climate change can be summarized as follows:

3.1) Climate

- The annual maximum temperature will increase in both the near and far future (+0.79 to +0.83 °C and +2.47 to +2.64°C).

- The annual minimum temperature will increase in both the near and far future (+0.69 to +0.73 °C and +2.51 to +2.60°C).

- The annual mean temperature will increase in both the near and far future (+0.81 to +0.84 °C and +2.54 to +2.66°C).

- The annual evapotranspiration will not change significantly in the near future (+2.18%) but it will increase in the far future (+8.07% to +8.23%)

- The annual rainfall of the Nan River Basin will increase in the both near and far future (+4.3% to +5.82% and +10.57% to 12.63%).

- The monthly rainfall for the near future will not change from the present rainfall pattern; it will tend to increase in terms of magnitude only. However, the Upper and Lower Nan River Basin will have a chance of a seasonal shift in rainfall pattern in the far future. The peak rainfall for the far future period will shift to August, while it occurs in September in the present period. The higher amount of rainfall will occur though the wet season.

3.2) Hydrological variables

- The annual water demand of both irrigation projects will not change significantly in either the near or far future (+1.21% to +4.54% and +1.1% to +6.41%).

- The water demand in the wet season will decrease (-3.38% to -21.75%) while in dry season it will increase (+3.05% to 21.19%) in both the near and far future period.

- The annual runoff of the Nan River Basin for the near future will not change significantly (+3.72% to +5.64), while for the far future it will increase (8.53% to 11.93%).

- The monthly inflow of Sikit Dam and the Lower Nan river Basin for the near and far future periods will not change from the existing runoff pattern; it will tend to increase in term of quantity only.

- The higher monthly lateral flow of the Middle Nan River Basin will occur in the early rainy season, however the runoff pattern will tend to increase in term of quantity only.

4) The impact assessment of the existing dam operations can be summarized as follows:

4.1) In near and far future, the inflow will increase by 5.64% and 11.93%, respectively.

4.2) In near and far future, the storage of general dam operation will increase by 7.93% and 12.7%, respectively, while the storage of flood dam operation will increase 3.20% and 5.75%, respectively.

4.3) In near and far future, the release of general dam operation will increase by 4.74% and 9.53%, respectively, while the release of flood dam operation will increase by 4.51% and 10.14%, respectively.

4.4) In the general dam operation, in near future, the water deficit per demand of PSK will decrease not significantly (-0.19%) but in far future it will increase by 1.04%. On the other hand, in near and far future, the water deficit per demand of CHY will increase by 3.53% and 1.67%, respectively.

For the flood dam operation, the water deficit per demand of PSK will decrease by 1.36% and 1.91%, respectively. On the other hand, in near and far future, the water deficit per demand of CHY will increase by 2.92% and 4.89%, respectively.

4.5) In the general dam operation, in near future, the maximum accumulative streamflow will decrease by -2.04% but in far future it will increase by 35.41%. On the other hand, the flood dam operation, in near and far future, the maximum accumulative streamflow will decrease by -31.92% and -16.72%, respectively.

4.6) Regarding the results of dam operation, the flood dam operation will cause less flood but it will cause more drought.

5) The impact assessment on the Plaichumphol O&M Project, it was found that the annual water deficit per demand in the near future will decrease by -7.14% while the annual water deficit per demand in the far future will not change significantly (-0.06).

6) The adaptation system to climate change was developed in the study (called ANFIS* reservoir operation). The system will result more water demand for the PSK and CHY irrigation projects. The storage of ANFIS* reservoir operation at the end of season will be higher than the other reservoir operations that cause the water demand decision making module determine more crop cultivation area.

7) The monthly storage of the ANFIS* reservoir operation rule will be between the monthly general and flood reservoir operation rules. The ANFIS* reservoir operation will store more water in the wet season to prepare more water for allocation during the dry season, and it will release more water in the dry season, which reduce water shortage, and result more space to allow more storage in the wet season. This ANFIS* will combine the advantage of the general rule and flood rule together.

8) The ANFIS* reservoir operation can reduce the spillage in the general case in present and near future periods; however, spillage will still occur in the extreme inflow case.

9) The ANFIS* reservoir operation can reduce the water deficit better than the general reservoir operation; however the water deficit per demand is closer to the general reservoir operation. Furthermore it can reduce the maximum water deficit better than the other reservoir operations.

10) The ANFIS* reservoir operation releases more water in both the wet and dry season and that causes higher seasonal runoff at the downstream runoff stations.

11) The ANFIS* reservoir operation can reduce the maximum accumulative runoff better than the general reservoir operation, however flood

reservoir operation still can reduce runoff more efficiently than other reservoir operations.

8.2 Recommendations

1) For the further study in of the GCM climate data, updated GCM climate data should be further conducted.

2) Finding a suitable membership function for formulating the ANFIS consumed a lot of time using trial and error method, and a genetic algorithm can be applied to solve this problem in the future.

3) Adjusting the cropping pattern with the climate change in each smaller zone should be considered for the adaptation scheme.

4) In the actual situation, the adaptive reservoir operation system can enhance more efficiently dealing with water shortage and flood problems by utilizing medium-term rainfall forecast (3 months ahead) as the input variable data. The forecasting rainfall can be found from the relationship between rainfall and SST Nino 3.4 (e.g. Chaowiwat and Koontanakulwong, 2012).

5) According to the impact assessment of the Plaichumphol O&M Project, it was found that improvement of water management can be accomplished by adjusting the ANFIS water allocation rules to find a suitable water demand.

6) If any extreme inflow happen in the future, the storage-release ratio in developed ANFIS* system should be revised to cope with the future flood situation because this ANFIS* was develop based on the historical storage and release data.

REFERENCES

Abe-Ouchi, A. et al., 1996 Outline of coupled atmosphere and ocean model and experiment. Internal report, Centre for Climate System Research, University of Tokyo, Japan.

Annamalai, H., K. Hamilton, K. R. Sperber, 2007: The South Asian Summer Monsoon and Its Relationship with ENSO in the IPCC AR4 Simulations. J. Climate, 20, 1071–1092. doi: http://dx.doi.org/10.1175/JCLI4035.1

Akiyuki, K., Masatsugu, T., Janet, H, Peter, R. and Srikantha, H., An integrated approach to evaluate potential impact of precipitation and land-use change on streamflow in Srepok River Basin, Theory and Applications of GIS, 2010, Vol.18, No.2, pp.9-20

Al-Faqih, L.; and others. Decision analysis applications for the sustainability of global urban water resources and drainage systems. WEFTEC

Bangkok Post. More flood mayhem on the way. Online news article. www.bangkokpost.com/news/local/259907/more-flood-mayhem-on-the-way. 10 June, 2011.

Bollasina, M., Nigam, S., Indian Ocean SST, evaporation, and precipitation during the South Asian summer monsoon in IPCC AR4 coupled simulations. Clim Dyn 33:1017–1032, 2009 doi:10.1007/s00382-008-0477-4.

Brekke, L.D., Maurer,E.P., Jamie D. Anderson,J.D., Dettinger, M.D., Townsley, E.S., Harrison, A. and Pruitt, T., Water Resources Research, VOL. 45, 2009. W04411, doi:10.1029/2008WR006941.

Burn HD, Simonovic SP.. Sensitivity of reservoir operation performance to climatic change. Water Resour Manage J, 10(6):463–78, 1996.

Busuioc, A.; Tomozeiu, R. ; and Cacciamani, C. Statistical downscaling model based on canonical correlation analysis for winter extreme precipitation events in the Emilia-Romagna region. Royal Meteorological Society, 2007.

Bryan, K., and L.J. Lewis, A Water Mass Model of the World Ocean, Journal of Geophysical Research, 84(C5):2503-2517, 1979.

Carroll DL. Chemical laser modelling with genetic algorithms. Amer Inst Aeronaut Astronaut (AIAA) J 1996;34(2):338–46.

Cavazos, T.; and Hewitson, B. Relative Performance of Empirical Predictors of Daily Precipitation.

Celeste, A.B. ; and other. Implicit stochastic optimization for deriving reservoir operating rules in semiarid brazil. Pesquisa Operacional, v.29, 1(2009) : 223-234.

Celeste, A.B, Billib M, Evaluation of stochastic reservoir operation optimization models, Adv Water Resour 32(9):1429–1443, 2009.

Chaleeraktrakoon, C. ; and Kangrang, A. Dynamic programming based approach for searching rule curves across multi-reservoir systems. Role of Water Sciences in Transboundary. River Basin Management, Thailand, 2005 : 121-129.

Chaowiwat, W. and Koontanakulvong S. Climate change impact on water resource management in East Coast Basin Thailand. Proc. 2nd Regional Conference on Global Environment Ho Chi Minh City, Vietnam March 8-9th , 2010.

Chaowiwat, W. and Koontanakulvong S. Statistical forecasting of rainfall with ENSO index in the Chao Phraya River Basin in Thailand, PAWEES 2012 International Conference Challenges of Water & Environmental Management in Monsoon Asia, November 27-29th, 2012.

Charles, S. P. ; Bari, M. A. ; Kitsios, A.; and Bates, B. C. Effect of GCM bias on downscaled precipitation and runoff projections for the Serpentine catchment, Western Australia. Royal Meteorological Society.

Chen, D. and others. Bias correction of an ocean-atmosphere coupled model. Geophysical Research Letters, Vol. 27, 16(2000) : 2585-2588.

Cheng, C. S. ; Li, G. ; Q. Li ; and Auld, H. Statistical downscaling of hourly and daily climate scenarios for various meteorological variables in South-central Canada. Theor. Appl. Climatol. 91(2008) : 129–147.

Chih-Chiang., W.; Li., C. and Hsun-Hsin., H. Neural-Based Decision Trees Classification Techniques: A Case Study in Water Resources Management, Recent Advances in Computer Science and Information Engineering, Lecture Notes in Electrical Engineering Volume 124, 2012, p. 377-382.

Chinvanno, S., Future Climate Projection for Thailand and Surrounding Countries : Climate Change Scenario of 21st Century, Regional Assessments and Profiles of Climate Change Impacts and Adaptation in PRC, Thailand and Viet Nam: Biodiversity, Food Security, Water Resources and Rural Livelihoods in the GMS , August 2009.

Chow, V.T., Maidment, D.R., and Mays, L.W. (1988). Applied hydrology. McGraw-Hill, New York, NY.

Clark, C.O. (1945). “Storage and the unit hydrograph.” Transactions, ASCE, 110, 1419-1446.

Collins, W. D., and Coauthors, 2006: The Community Climate System Model Version 3 (CCSM3). J. Climate, 19, 2122–2143.

Corral, C. ; and other, A distributed rainfall runoff model to use in mediterranean basins with radar rainfall estimates, 2001Davis, W.Y. Water Demand Forecast Methodology for California Water Planning Areas - Work Plan and Model Review. Cal-Fed Bay Delta Program , California Bay-Delta Authority, 2003

Delworth, T. L., and Coauthors, 2006: GFDL's CM2 Global Coupled Climate Models. Part I: Formulation and simulation characteristics. J. Climate, 19, 643–674.

Diskin, M. H., & Simon, E. A procedure for the selection of objective functions for hydrologic simulation models, Journal of Hydrology 34, 129-149, 1977.

Dix, M. R., and Hunt, B. G. Transient climatic change to 3 x CO2 conditions. Global and Planetary Change, 18 (1-2): 15-36, 1998.

Donald, H. B.; and Simonovic, S.P.Sensitivity of Reservoir Operation Performance to Climatic Change. Water Resources Management 10: 463-478, 1996.

Doria, R.; Madramootoo, C. A.; and Mehdi, B. B. Estimation of Future Crop Water Requirements for 2020 and 2050, Using CROPWAT ,2006.

DWR, Executive Summary, Formulation of integrated plan for water resources management in Nan river basin, 2005.

DWR, Executive Summary, Formulation of integrated plan for water resources management in Yom river basin, 2005.

Electricity Generating Authority of Thailand, (2004) Manual for operating the Bhumibol andSirikit Reservoirs. EGAT Research Report., Bangkok, Thailand. (in Thai).

Electric Generation Authority of Thailand, (2010) Parallel Reservoirs operation Improvement Project for Bhumibol and Sirikit Dams, December. (in Thai).

Elshamy, M. E.; Seierstad, I. A.; and Sorteberg, A. Impacts of climate change on Blue Nile flows using bias-corrected GCM scenarios. Hydrology and Earth System Sciences Discussions, 5 (2008) : 1407–1439.

EM-DAT: The OFDA/CRED International Disaster Database, www.emdat.be -Université catholique de Louvain - Brussels – Belgium. Version 12.07. Aug 2012.

Flato, G.M. and Hibler, W.D. III, 1992: Modelling Pack Ice as a Cavitating Fluid. J. Phys. Oceanogr., 22, 626-651.

Fowler, H. J. ; Blenkinsop, S. ; and Tebaldi, C. Review Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. International Journal of Climatology. 27(2007) : 1547–1578

Frich, P., L. V. Alexander, P. Della-Marta, B. Gleason, M. Haylock, A. M. G. Klein Tank, and T. Peterson, 2002: Observed coherent changes in climatic extremes during the second half of the twentieth century. Climate Res., 19, 193–212.

Fukami, K.; Fujiwara, N.; Ishikawa, M.; Kitano, M.; Kitamura, T.; Shimizu, T. ; Hironaka, S.; Nakamura, S.; Goto, T.; Nagai, M. and Tomita, S. “Development of an integrated flood runoff analysis system for poorly-gauged basins”, Proceeding of the 7th International Conference on Hydroinfomatics (HIC2006), 4(2006) : 2845-2852.

Gadgil S, Sajani S, Monsoon precipitation in the AMIP runs. Clim Dyn 14:659–689; 1998.

Gen M, Cheng R. Genetic algorithms and engineering optimization. New York: John Wiley & Sons; 2000.

Georgakakos, A.P., Yao, H., Kistenmacher M., Georgakakos, K.P., Graham, N.E. and Cheng, F.Y..Value of adaptive water resources management in Northern California under climatic variability and change: Reservoir Management. Journal of Hydrology 412–413, 34–46, 2012.

Ghosh, S. ; and Mujumdar; P.P. Statistical downscaling of GCM simulations to streamflow using relevance vector machine. Advances in Water Resources. 31 (2008) 132–146

Goldberg DE, Richardson J. Genetic algorithms with sharing for multimodal function optimization. In: Genetic algorithms and their applications: Proc of the second international conference on genetic algorithms. 1987. p. 41–9.

Graham, L. P., J. Andréasson, and B. Carlsson, Assessing climate change impacts on hydrology from an ensemble of regional climate models, model scales and linking methods—A case study on the Lule River basin, Clim. Change, 81(S1), 293–307, (2007) doi:10.1007/s10584-006-9215-2.

Gugiura, T.; and other. Development of integrated flood analysis system (ifas) and its applications . Infrastructure Development Institute (IDI), Japan.

Hanasaki, N., Kanae, S., Oki T. and Musiake, K. Simulating the discharge of the Chao Phraya River taking into account reservoir operation, Water Resources System Hydrological Risk, Management and Development, 281, pp.215-223, 2003.

Harboe, R. ; and Ratnayake, U. Simulation of a reservoir with standard operating rule. Extreme Itydroloeical Events: Precipitation, Floods and Droughts (Proceedings of the Yokohama Symposium, July 1993). IAHS Pubf. no. 213, (1993). 421-428.

Harboe, R. Optimal power output for operation of a reservoir system, Proc. VII Congress of the Asian and Pacific Division (IAHR), Beijing, China, Vol II (1990), 171-174.

Harrouni KEl, Ouazar D, Walters GA, Cheng AH-D. Groundwater optimisation and parameter estimation by genetic algorithm and dual reciprocity boundary element method. Eng Anal Boundary Elements 1996;18:287–96.

Harvey, H. ; Hall, J. W. ; and Peppé, R.Outline of a framework for systematic decision analysis in flood risk management. 18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009 : 4290-4297.

Hashino, T.; Bradley, A. A.; and Schwartz, S. S. Evaluation of bias-correction methods for ensemble streamflow volume forecasts. Hydrology and Earth System Sciences Discussions. 3 (2006) : 561–594.

Hernandez, M. ; and other. Modeling runoff response to land cover and rainfall spatial variability in semi-arid watersheds. Environmental Monitoring and Assessment 64(2000) : 285–298.

Hidalgo, H. G., Dettinger, M. D., and Cayan, D. R. 2008 : Downscaling with constructed analogues: daily precipitation and temperature fields over the United States., California Energy Commission, Public Interest Energy Research Program, Sacramento, CA, 62 pp.

Hoffmann, M., Worthington, A.; and Higgs, H. Modeling residential water demand with fixed volumetric charging in a large urban municipality: The case of Brisbane, Australia 1-12, 2002.

Hunukumbura, P. B. and Tachikawa, Y.. River Discharge Projection under Climate Change in the Chao Phraya River Basin, Thailand, Using the MRI-GCM3.1S Dataset. Journal of the Meteorological Society of Japan, Vol. 90A, pp. 137--150, 2012.

Hydrologic Engineering Center. Hydrologic modeling system HEC-HMS: User’s manual. Version 3.0.0. Davis, CA: U.S. Army Corps of Engineers, 2005.

Ines, V.M. and Hansen, J. W. Bias correction of daily GCM rainfall for crop simulation studies. Agricultural and Forest Meteorology. 138 (2006): 44–53.

Inomata H., Takeuchi K. and Fukami K.: Development of a statistical bias correction method for daily precipitation data of GCM20, Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering), Vol. 67, No. 4, I_247-I_252, 2011.

IPCC, 2007: Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Janeiro a Abril de Celeste, A.B. ; and Billib, M. Evaluation of stochastic reservoir operation optimization models. Advances in Water Resources 32 (2009) 1429–1443

Jensen, M.E.; Burman, R.D.; and Allen, R.G. (eds). Evapotranspiration and irrigation water requirements. ASAE, New York, New York. (1990)

JIID, The Impact of Climate Change on Irrigation Systems and Adaptation Measures (Dam Operation Analysis), Final Report, February 2013.

Jiang, S. Application of stochastic differential equations in risk assessment for flood releases . HydrologicalSciences—Journal—des Sciences Hydrologiques, 43(3) June 1998 : 349-360.

Johns, T. C., and Coauthors, 2006: The New Hadley Centre Climate Model (HadGEM1): Evaluation of coupled simulations. J. Climate, 19, 1327–1353.

Kaczmarek Z.. Impact of climatic variations on storage reservoir systems. Working paper, WP-90-020, international institute for applied systems analysis (IIASA), Laxenburg, Austria, p. 35, 1990.

Komori, D., Nakamura, S., Kiguchi, M., Nishijima, A., Yamazaki, D., Suzuki, S., Kawasaki, A., Oki, K., Oki, T., Characteristics of the 2011 Chao Phraya River flood in Central Thailand, Hydrological Research Letters 6, 41–46, 2012

Kangrang, A. ; Phumphan, A. and Chaiyapoom, W. Stochastic Inflow Simulation for Searching Rule Curves. American Journal of Applied Sciences 5 (3): 221-226, 2008.

Kang, I.-S., Jin, B. Wang, K.-M. Lau, J. Shukla, V. Krishnamurthy, S.D. Schubert, D.E. Wailser, W.F. Stern, A. Kitoh , G.A. Meehl, M. Kanamitsu, V.Y. Galin, V. Satyan, C.-K. Park, Y. Liu, Intercomparison of the climatological variations of Asian summer monsoon precipitation simulated by 10 GCMs, Climate Dynamics (2002) 19: 383–395, DOI 10.1007/s00382-002-0245-9

Kang, H. and other. Multimodel output statistical downscaling prediction of precipitation in the Philippines and Thailand. Geophysical Research Letters, VOL. 34 (2007)

Kazuhiko F. and Hironori I. ICHARM' s research activities for climate change analysis and adaptation : Kakushun Project & IFAS development, International Center for Water Hazard and Risk Management under the auspices of UNESCO (UNESCO_ICHARM), Public Works Research Insititute, JP.

Kim, S., Tachikawa, Y., Nakakita, E. and Takara, K.. Reconsideration of reservoir operations under climate change: case study with Yagisawa dam, Japan. Annual Journal of Hydraulic Engineering, JSCE, Vol.53, P.115 – 120, February 2009.

Kitoh, A., Kusunoki, S., East Asian summer monsoon simulation by a 20-km mesh AGCM, Clim Dyn (2008) 31:389–401. DOI 10.1007/s00382-007-0285-2

Koontanakulvong S., Chaowiwat W. (2011) GCM Data Comparison and its application to water disaster adaptation measures in Thailand. Technical Report, Chulalongkorn University, March.

Koontanakulvong S., Chaowiwat W. (2013) Climate Change Impact on Irrigation System and Farmers' response, Paddy Water Environ., July 2013.

Kripalani, R. H., Oh, J. H. Kulkarni, A. Sabade, S. S. and Chaudhari, H. S., South Asian summer monsoon precipitation variability: Coupled climate model simulations and projections under IPCC AR4, Theor. Appl. Climatol. 90, 133–159 (2007) DOI 10.1007/s00704-006-0282-0

Kumar, D.N.; Raju, K.S. ; andAshok, B. Optimal Reservoir Operation for Irrigation of Multiple Crops Using Genetic Algorithms. Journal of irrigation and drainage engineering , 2006 : 123-129

Lanza, L.G. ; Ramírez, J.A. ; and Todini, E. Stochastic rainfall interpolation and downscaling. Hydrology and Earth System Sciences, 5(2) (2001) : 139–143.

Lauri, H., de Moel, H., Ward, P. J., Rasanen, T. A., Keskinen, M. and Kummu, M., Future changes in Mekong River hydrology: impact of climate change and reservoir operation on discharge, Hydrol. Earth Syst. Sci., 16, 4603–4619, 2012.

Lin, J.L., Weickmann, K.M., Kiladis, G.N., Mapes, B.E., Schubert, S.D., Suarez, M.J., Bacmeister, J.T., Lee, M.I., Subseasonal variability associated with the Asian Summer monsoon simulated by 14 IPCC AR4 coupled GCMs. J Clim 21:4541–4567, 2008. doi:10.1175/2008JCLI1816.1

Maskey, S, Guinot, V, Roland K. Treatment of precipitation uncertainty in rainfall-runoff modelling: a fuzzy set approach. Advances in Water Resources 27 (2004) : 889–898

Manabe,S., Stouffer,R.J., Spelman,M.J. and Bryan,K. Transient response of a coupled ocean-atmosphere model to gradual changes of atmospheric CO2. Part I: annual-mean response J. Climate, 4, 785-818, 1991.

Maurer, E. P.; and Hidalgo, H. G. Utility of daily vs. monthly large-scale climate data: an intercomparison of two statistical downscaling methods. Hydrol. Earth Syst. Sci. Discuss., 4(2007), 3413–3440.

Magome, J.; and others. Flood risk forecasting for poorly gauged basins in the Mekong river basin using a distributed hydrological model and a satellite derived precipitation dataset 6th Annual Mekong Flood Forum (AMFF-6)1-8.

Mamdani, E.H. Application of fuzzy algorithms for simple dynamic plant. Proc. IEE 121: 1585–1588, 1974.

Mamdani, E.H. and Assilian, S. An experiment in linguistic synthesis with a fuzzy logic controller. Int. J. Man Mach. Studies 7(1): 1–13, 1975.

Mehrotra, R., and A. Sharma, A nonparametric stochastic downscaling framework for daily rainfall at multiple locations. Journal of Geophysical Research-Atmospheres, 111, 2006.

Monteith, J.L. Evaporation and environment. Symposia of the Society for Experimental Biology 19: 205–224, 1965.

Murphy, C.; and other. Scatering for uncertainty in a conceptual rainfall runoff model: Model preparation for climate change impact assessment and the application of glue using latin hypercube sampling. National Hydrology Seminar 2004 : 64-74.

Mylopoulos, Y. A. ; and Mylopoulos, N. A. Economic incentives in sustainable water management: a risk - based decision analysis approach for determining groundwater pollution charges under uncertainty. Global Nest: the Int. J. Vol 1, 3(1999): 205-215.

Nakicenovic, N, Swart R. Special Report on Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge, UK and New York. 570 p., 2000.

Nixon JB, Dandy GC, Simpson AR. A genetic algorithm for optimising off-farm irrigation scheduling. J Hydroinformatics 2001;3:11–22.

Palomo, J. ; Insua D. R. ; and Salewicz, K.A. Reservoir Management Decision Support. Integrated Assessment and Decision Support Proceedings of the 1st Biennial Meeting of the iEMSs, 2002.

Pappenberger F. ; and others Cascade model uncertainty from medium range weather forecasts (10 days) through a rainfall-runoff model to flood inundation predictions within the European Flood Forecasting System (EFFS). Hydrology and Earth System Sciences, 9(4), (2005) : 381-393.

Pappenberger, F. ; and Beven, K. Uncertainty analysis of the rainfall runoff model LisFlood within the Generalized Likelihood Uncertainty Estimation (GLUE) . Intl. J. River Basin Management Vol. 2, 2 (2004) : 123–133.

Pawlowsky MA. Crossover operations. In: Chambers L, editor. Practical handbook of genetic algorithms, applications, vol. 1. Boca Raton: CRC Press; 1995. p. 101–14.

Piani, C. ; Haerter, J. O. ; and Coppola, E. Statistical bias correction for daily precipitation in regional climate models over Europe. 2009.

Piper, B. S. and other. Technical Communication Chi River Basin Irrigation Demand Model. Water Resources Management 3(1989) : 155-163.

Pinthong, P., Ashim D. G., Mukand S. B., and Weesakul S. Improved Reservoir Operation Using Hybrid Genetic Algorithm and Neurofuzzy Computing, Water Resour Manage (2009) 23:697–720.

Rajeevan, M., Unnikrishnan CK, Preethi B (2012) Evaluation of the ENSEMBLES multi-model seasonal forecasts of Indian summer monsoon variability. Clim Dyn 38:2257–2274. doi:10.1007/s00382-011-1061-x

Ratnayake, U. & Harboe, R. Optimal operating rule for a reservoir with stochastic inflows, Proc. VIII Congress of the Asian and Pacific Division (IAHR), Pune, India. (1992)

Ratnayake, U; and Harboe, R.Deterministic and Stochastic Optimization of a Reservoir System. International Water Resources Association, Water International, Volume 32, 1(2007), :155-162.

Revelli R, Ridolfi L. Fuzzy approach for analysis of pipe network. J Hydraulic Eng 2002;128(1):93–101.

Renwick, M. ; and Archibald, S. Demand side management policies for residential water use: Who bears the conservation burden?. Land Economics, vol. 74, 3 (1998) : 343-359.

Renwick, M. A. ; and Green, R. D.. Do Residential Demand Side Management Policies Measure Up? An Analysis of Eight California Water Agencies. Journal of Environmental Economics and Management. 40 (2000) : 37-55.

RID, The feasibility of mitigation Yom-Nan river project, 2005

Roeckner,E., Arpe,K., Bengtsson,L., Christoph,M., Claussen,M., Dümenil,L., Esch,M., Giorgetta,M., Schlese,U. and Schulzweida,U. The atmospheric general circulation model ECHAM-4: model description and simulation of present-day climate Max-Planck Institute for Meteorology, Report No.218, Hamburg, Germany, 90pp, 1996.

Royal Irrigation Department (2012), The improvement of reservoir operation report, The committee of main dams management planning and water management planning of the year 2012, March 2012.

RID, The Status of Nan river basin, 2000.

RID, The Status of Yom river basin, 2000.

Rittima, A.Hedging Policy for Reservoir System Operation: A Case Study of Mun Bon and Lam Chae Reservoirs. Kasetsart J. (Nat. Sci.) 43 : 833 - 842 (2009)

Russell, S. O., Kenning, B. F. I., and Sunnell, G. J. 1979.“Estimating Design Flows for Urban Drainage,” Journal Hydraulics Division, American Society of Civil Engineers,Vol 105, No. HY1, pp 43-52.

Satoh, M. and A.Kabawata.. Reservoir operation Principles for stable water in the Mae Klong River Basin. Workshop on sustainable management Of The Mae Klong River Basin, Thailand.(1999).

Schneider SH, Semenov S, Patwardhan A, Burton I, Magadza CHD, Oppenheimer M, Pittock AB, Rahman A, Smith JB, Suarez A, Yamin F 2007 : Assessing key vulnerabilities and the risk from climate change. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp 779–810.

Schulz K, Huwe B. Water flow modelling in the unsaturated zone with imprecise parameters using a fuzzy approach. J Hydrol 1997;201:211–29.

Sen, Z. 1998. Fuzzy algorithm for estimation of solar irradiation from sunshine duration. Solar Energy 63(1): 39-49.

Sen, Z. 2004a. Genetik Algoritmalar ve Eniyileme Yöntemleri. (Genetic Algorithms and Optimization Methods). Su Vakfi Yayinlari (Turkish Water Foundation Publication), 235 pp. (in Turkish).

Sen, Z. 2004b. Yapay Sinir Agˇları ˙Ilkeleriç (Artificial Neural Network Principles). Su Vakfı yayınları Yayınları (Turkish Water Foundation Publication), 285 pp. (in Turkish).

Sen, Z. Fuzzy logic and hydrological modeling, Taylor and Francis Group, LLC, 2010.

Sharma, D. ; Gupta D.A. ; and Babel, M. S. Spatial disaggregation of bias-corrected GCM precipitation for improved hydrologic simulation: Ping River Basin, Thailand . Hydrology and Earth System Sciences Discussions, 4 (2007): 35–74.

Smith, M., Allen, R. G., Monteith, J. L., Pereira; L. S., Perrier, A., Pruitt, W. O. 1992. Report on the Expert Consultation on procedures for Revision of FAO Guidelines for Prediction of Crop Water Requirements. Land and Water Development Division, United Nations Food and Agriculture Service, Rome, Italy.

Sperber, K. R., T. N. Palmer, Interannual Tropical Rainfall Variability in General Circulation Model Simulations Associated with the Atmospheric Model Intercomparison Project. J. Climate, 9, 2727–2750,1996.

Sperber, K. R., Annamalai, H., Kang, I.-S., Kitoh, A., Moise, A., Turner, A., Wang, B., Zhou, T., The Asian summer monsoon: an intercomparison of CMIP5 vs. CMIP3 simulations of the late 20th century, Clim Dyn (2013) 41:2711–2744, DOI 10.1007/s00382-012-1607-6

Soltani, M.A. ; and otherStochastic Multi-Purpose Reservoir Operation Planning by ScenarioOptimization and Differential Evolutionary Algorithm. Journal of Applied Sciences 8 (22): 4186-4191, 2008

Stedinger, J.R.1984. The Performance Of LDR models For preliminary design and reservoir operation. Water Resour. Res .20(2):215-224.

Sharma, D. Downscaling of general circulation model precipitation for assessment of impact on water resources at basin level, Asian Institute of Technology, December, 2007.

Shrestha, R.K.; Yasuto Tachikawa, Y. ; and Takara, K.Downscaling Spatial Rainfall Field from Global Scale to Local Scale Using Improved Multiplicative Random Cascade Method. Annuals of Disas. Prev. Res. Inst., Kyoto Univ., No. 47, 2004.

Stouffer, R.J., Manabe,S. and Vinnikov,K.Ya. 1994 Model assessment of the role of natural variability in recent global warming Nature, 367, 634-636.

Sugeno, M., Ed. 1985. Industrial Applications of Fuzzy Control, North-Holland, New York.

Sugiura, Development of Integrated Flood Analysis System (IFAS) and its applications, Proceedings of the 8th International Conference on Hydroinfomatics, January 12-16, 2009 Concepción Chile 2009, Concepción, Chile.

Tantanee, S. and other.Downscaled Rainfall Prediction Model (DRPM) using a Unit Disaggregation Curve (UDC). Hydrology and Earth System Sciences Discussions, 2(2005) : 543–568.

Trigo, R. M., R. García-Herrera, J. Díaz, and I. F. Trigo, 2005: How exceptional was the early August 2003 heat wave in France? Geophys. Res. Lett., 32, L10701, doi:10.1029/2005GL022410.

Uhlenbrook, S. Prediction uncertainty of conceptual rainfall runoff models caused by problems in identifying model parameters and structure. Hydrological Sciences-Joumal-des Sciences Hydrologiques, 44(5) October 1999 : 779-797

Ungersbock, M. ; Rubel, F. ; Fuchs, T. ; and Rudolf, B. Bias correction of global daily rain gauge measurements. Physics and Chemistry of the Earth, 26, 411-414

USACE. HEC-HMS Hydrologic modeling system user’s manual. Hydrologic Engineering Center, Davis, CA, 2005.

Vonnarart, O., Pasak Jolasid reservoir operation by Artificial Neural Network Technique application, Department of water resources engineering, Faculty of engineering, Chulalongkorn University, 2003.

Vudhivanich, V.; and Rittima, A. Development of Probability Based Rule Curves for a Reservoir . Kasetsart J. (Nat. Sci.) 37(2003) : 234 – 242.

Vudhivanich, V. Applied Hydrology. Irrigation Engineering Department, Faculty of Engineering, Kasetsart University, Bangkok, 494 p., 1998.

Waliser D.E., Jin, K., Kang. I.S., Stern, W.F., Schubert, S.D., Wu, M.L.C., Lau, K.M., Lee, M.I., Krishnamurty, V., Kitoh, A., Meehl, G.A., Galin, V.Y., Satyan, V., Mandke, S.K., Wu, G., Liu, Y., Park, C.K., AGCM simulations of intraseasonal variability associated with the Asian summer monsoon. Clim Dyn 21:423–446, 2003 doi:10.1007/s00382-003-0337-1

Watanabe, S., Kanae, S., Seto, S., Yeh, P. J. F., Hirabayashi, Y.,1and Oki, T., Intercomparison of bias-correction methods for monthly temperature and precipitation simulated by multiple climate models, Journal of Geophysical Research, Vol. 117, D23114 , 2012.

Wetterhall, F. and othersStatistical downscaling of daily precipitation over Sweden using GCM output. Theor Appl Climatol. 96(2009) :95–103.

Wilk, J.; and Hughes, D. A. Calibrating a rainfall-runoff model for a catchment with limited data. Hydrological Sciences- Jour-nal-des Sciences Hydrologiques. 47(1) February 2002, 3-17.

Zehe, E. ; Singh, A. K.; and Bardossy, A.Prediction of monsoon rainfall for a mesoscale Indian catchment based on stochastical downscaling and objective circulation patterns. Hydrol. Earth Sys. Sci. Discuss., 2(2005), 1961–1993.

APPENDIX

Appendix A

Basic data for water resources analysis

A.1 The emission scenarios of the IPCC special report on emission scenarios (SRES)

Emission scenarios are not assessed in this Working Group I Report of the IPCC. This box summarizing the SRES scenarios is taken from the TAR and has been subject to prior line-by-line approval by the Panel.

A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil-intensive (A1FI), non-fossil energy sources (A1T) or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end technologies).

A2. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

B1. The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

Table A.1 Selected Rainfall Stations in Nan River Basin

Station	Name	Amphoe	Changwat	Latitude	Longitude	Period
26022	A. Chumsaeng	Chumsang	Nakhonsawan	15-52-48	100-18-22	1994 - 2011
28013	A. Muang	Muangnan	Nan	18-46-35	100-46-26	1920 - 2011
28022	A. Sa	Wengsa	Nan	18-34-10	100-45-14	1996 - 2011
28032	A. Na Noi	Nanoy	Nan	18-19-34	100-43-01	1994 - 2011
28042	A. Pua	Pua	Nan	19-10-57	100-55-01	1994 - 2011
28053	A. Thung Chang	Thungchang	Nan	19-23-11	100-52-48	1920 - 2011
28062	Mae Sakhon Forest Protected Station Unit5	Wengsa	Nan	18-32-00	100-45-00	1999 - 2011
28073	A. Tha Wang Pha	Thawangpha	Nan	19-07-04	100-48-47	1968 - 2011
28102	A. Chiang Klang	Chengklang	Nan	19-17-33	100-51-58	1970 - 2011
28111	Ban Hat Khao San (N.42)	Wengsa	Nan	18-34-05	100-52-26	1977 - 2011
28131	Yan Sarung (N.35)	Nanoy	Nan	18-23-46	100-51-04	1969 - 1991
28142	Nan Agrometeorological Station	Muangnan	Nan	18-52-00	100-45-00	1975 - 2011
28152	A. Mae Charim	Maecharim	Nan	18-44-00	101-01-01	1981 - 2011
28164	Doi Phu Ka, A. Pua	Pua	Nan	19-11-52	100-59-35	1991 - 2011
28172	K.A. Song Khwae	Sangkwae	Nan	19-21-32	100-42-22	1992 - 2011
36052	A. Chon Daen	Chondan	Phetchaboon	16-11-15	100-51-47	1997 - 2011
36104	Pine Camp	Khaokor	Phetchaboon	16-45-57	101-02-02	1997 - 2011
36155	Huai Ngaet	Wangthong	Phisanulok	16-48-06	100-54-04	1983-1995
36162	Khao Ya Palace	Khaokor	Phetchaboon	16-33-03	100-58-44	1986 - 2011
36172	A. Wang Pong	Wangpong	Phetchaboon	16-20-20	100-47-49	1986 - 2011
36202	Khao Kho Agrometeorological Station	Khaokor	Phetchaboon	16-37-36	100-59-56	1995 - 2011
36342	Ban Lao Ya School	Khaokor	Phetchaboon	16-45-55	101-01-59	1995 - 2011
38012	A. Muang	Muangpichit	Phichit	16-26-12	100-21-14	1994 - 2011
38022	A. Bang Mun Nak	Bangmunnak	Phichit	16-01-35	100-23-56	1996 - 2011
38042	A. Taphan Hin	Tapanhin	Phichit	16-12-44	100-25-34	1957 - 2011
38072	A. Wang Sai Phun	Wangsaipoon	Phichit	16-25-00	100-33-00	1979 - 2011
38082	Khao Sai School	Thup khlo	Phichit	16-10-00	100-33-00	1983 - 2011
38092	Phitchit Agrometeorological Station	Maungphichit	Phichit	16-26-10	100-17-20	1994 - 2011
39013	A. Muang	Maung Phitsanulok	Phisanulok	16-49-24	100-15-43	1920 - 2011
39032	A. Wang Thong	Wangthong	Phisanulok	16-49-25	100-25-59	1994 - 2011
39042	A. Nakhon Thai	Nakhonthai	Phisanulok	17-05-56	100-50-31	1994 - 2011
39052	A. Phrom Phiram	Phompiram	Phisanulok	17-02-56	100-12-14	1994 - 2011
39062	A. Bang Krathum	Bangkrathum	Phisanulok	16-34-40	100-18-11	1999 - 2011
39072	A. Wat Bot	Watbod	Phisanulok	16-59-34	100-18-43	1999 - 2011
39082	Phitsanulok Agriculture Experimental Station	Maung Phitsanulok	Phisanulok	16-51-00	100-21-00	1962 - 2011

Table A.1 Selected Rainfall Stations in Nan River Basin (continued)

Station	Name	Amphoe	Changwat	Latitude	Longitude	Period
39091	Ban Yang (N.22)	Wat Bot	Phisanulok	17-01-57	100-22-23	1965 - 1982
39101	Wang Nok Aen (N.24)	Wang Thong	Phisanulok	16-50-35	100-31-19	1965 - 2011
39132	Khao Krayang Forest Plantation	Wang Thong	Phisanulok	16-52-00	100-45-00	1969 - 2011
39142	A. Chattrakan	Chadthakarn	Phisanulok	17-17-00	100-33-00	1973 - 2011
39151	Nan River Alter Condition Unit (N.5A)	Maung Phitsanulok	Phisanulok	16-49-15	100-15-50	1973 - 2011
39161	Ban Nong Bon (N.40)	Wat Bot	Phisanulok	17-13-14	100-21-11	1978 - 2011
39175	Ban Pong Bon	Wang Thong	Phisanulok	16-51-04	100-36-58	1980 - 2002
39180	Naresuan Dam	Phrom Phiram	Phisanulok	17-02-50	100-10-52	1981 - 1993
39202	Phu Miang and Phu Thong	Chattrakan	Phisanulok	17-23-02	100-34-44	1991 - 2011
39210	Phitsanulok Irrigated Water Uses Exp.and Research	Phompiram	Phisanulok	17-02-46	100-11-10	1986 - 1994
39220	Hydrological Center 2	Maung Phitsanulok	Phisanulok	16-47-28	100-12-20	1997 - 2011
59162	A. Si Nakhon	Srinakhon	Sukothai	17-27-00	99-58-00	1976 - 2011
70013	A. Muang	Muanguttharadit	Uttaradit	17-37-32	100-05-56	1920 - 2011
70022	A. Nam Pat	Nam Pad	Uttaradit	17-43-35	100-41-17	1994 - 2011
70032	A. Laplae	Luplae	Uttaradit	17-39-00	100-02-33	1994 - 2011
70042	A. Phichai	Pichai	Uttaradit	17-17-04	100-05-28	1994 - 2011
70052	A. Tron	Tron	Uttaradit	17-28-53	100-07-01	1994 - 2011
70062	A. Tha Pla	Thapla	Uttaradit	17-47-26	100-22-52	1994 - 2011
70072	A. Fak Tha	Fak Tha	Uttaradit	17-59-25	100-52-55	1994 - 2011
70131	Ban Fai (N.16)	Nam Pat	Uttaradit	17-44-24	100-42-00	1979 - 1981
70151	Hat Phai (N.12A)	Tha Pla	Uttaradit	17-44-10	100-32-28	1966 - 2011
70170	Nam Rit R.I.D. Office	Muang Uttaradit	Uttaradit	17-37-38	100-06-32	1970 - 1989
70180	Nam Pat Headwork	Fak Tha	Uttaradit	18-02-41	100-55-19	1970 - 1990
70192	Nan River Self-supporing Settlement	Muang Uttaradit	Uttaradit	17-45-00	100-16-59	1977 - 2011
70202	A. Ban Khok	Ban Kok	Uttaradit	18-02-58	101-01-41	1984 - 2011
70212	A. Thong Saen Khan	Thong San khun	Uttaradit	17-27-39	100-21-14	1985 - 2011
70221	Hat Song Khwae (N.60)	Tron	Uttaradit	17-24-50	100-07-52	1987 - 2011
70232	Phak Tha Cooperative Settlement	Fak Tha	Uttaradit	17-54-19	100-49-37	1989 - 2011
70242	Phu Soi Dao National Park	Nam Pat	Uttaradit	17-44-45	100-59-02	1993 - 2011
378201	A. Muang	Maung Phitsanulok	Phisanulok	16-49-24	100-15-43	1920 - 2011

Table A.2 Selected Runoff Stations in Nan River Basin

Station	Name	Amphoe	Changwat	Latitude	Longitude	Period
N.1	Nan at Forestry Office	Muangnan	Nan	18-46-23	100-46-52	1922-1953,1963-2011
N.2B	Nan at Ban Mon Mai	Muang Uttaradit	Uttaradit	17-36-30	100-06-07	1975-1981,1994-1995
N.5A	Nan at Muang	Maung Phitsanulok	Phitsanulok	16-49-15	100-15-50	1966-2011
N.7	Nan at Phichit	Muang Phichit	Phichit	16-26-31	100-21-11	1944-1949,1951-2000
N.7A	Ban Rat Chang Kwan	Muang Phichit	Phichit	16-28-03	100-20-05	2011
N.8A	Ban Ho Krai	Bangmunnak	Phichit	16-04-45	100-24-00	2011
N.10A	Nan at Taphan Hin	Tapanhin	Phichit	16-12-42	100-25-01	1978-1984,1986-1987,1991-2011
N.12A	Nan at Ban Hat Phai	Thapla	Uttaradit	17-44-10	100-32-28	1966-2011
N.13A	Nan at Highway Bridge (Ban Bun Nak)	Wengsa	Nan	18-33-12	100-46-08	1987-2011
N.14A	Nan at Wat Luang Pho Kaeo	Chumsang	Nakhonsawan	15-53-56	100-18-32	1978-1981,1991-2011
N.22	Khwae Noi at Ban Yang	Watbod	Phitsanulok	17-01-57	100-22-23	1963-1982,1996-2011
N.24	Nam Khek at Ban Wang Nok Aen	Wangthong	Phitsanulok	16-50-35	100-31-19	1965-2011
N.27A	Nan at Phrom Phiram	Phompiram	Phitsanulok	17-01-54	100-11-06	1980-2011
N.36	Khwae Noi at Ban Nong Krathao	Nakhonthai	Phitsanulok	17-04-59	100-49-55	1968-1987,1989-1989,1991-2011
N.40	Khwae Noi at Ban Nong Bon	Watbod	Phitsanulok	17-13-14	100-21-11	1977-2011
N.49	Nam Yao at Highway Bridge (Ban Nam Yao)	Pua	Nan	18-59-29	100-56-31	1979-2011
N.53	Khlong Butsabong at Ban Huai Tum	Chondan	Phetchaboon	16-11-26	100-55-41	1979-2011
N.55	Nam Phak at Ban Tha Sakae	Chadthakarn	Phitsanulok	17-15-10	100-37-52	1994-2011
N.58	Nam Fua at Ban Kok Muang	Nakhonthai	Phitsanulok	17-08-33	100-56-06	1998-2011
N.59	Lam Nam Khan at Ban Na Chan	Nakhonthai	Phitsanulok	17-01-43	100-50-46	1996-2011
N.60	Nan at Ban Hat Song Khwae	Tron	Uttaradit	17-24-50	100-07-52	1986-2011
N.63	Nam Haeng at Highway Bridge (Ban Hua Muang)	Nanoy	Nan	18-21-48	100-43-41	1987-2011
N.64	Nan at Ban Pha Khwang	Muang Nan	Nan	19-00-31	100-47-17	1994-2011
N.65	Huai Nam yao at Ban Pang Sa	Thawangpha	Nan	19-13-47	100-45-25	1996-2011
N.66	Huai Om Sing at Ban Om Sing Nua	Nakhonthai	Phitsanulok	17-07-17	100-53-49	1996-2011
N.67	Nan at Ban Goey Chai	Chumsang	Nakhonsawan	15-52-04	100-16-01	1997-2011
N.69	Khwae Noi at Ban Na Thung Yai	Nakhonthai	Phitsanulok	17-18-57	100-51-11	1999-2011

Appendix B

The change evaluation on hydrological variables

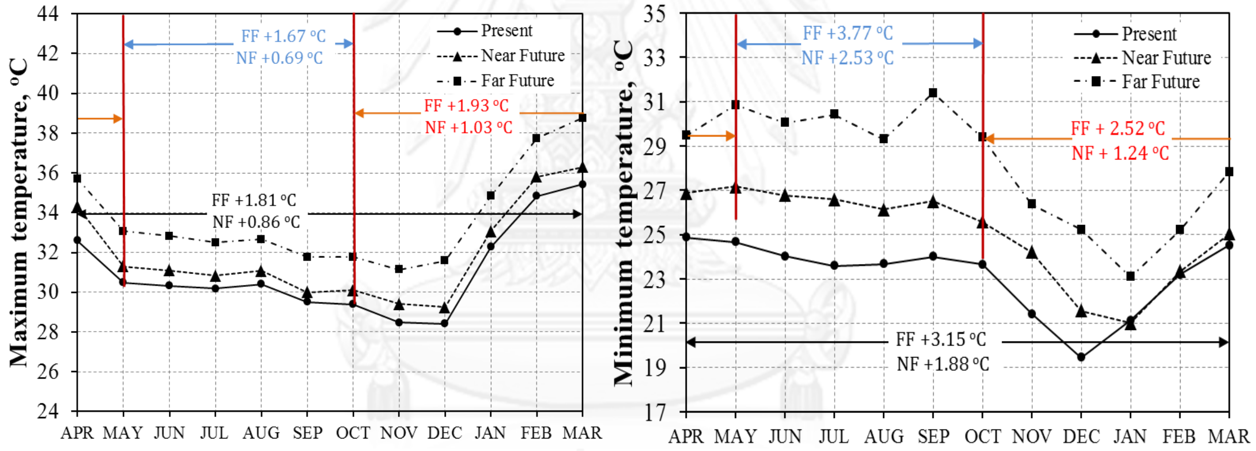
Appendix B

The change evaluation on hydrological variables

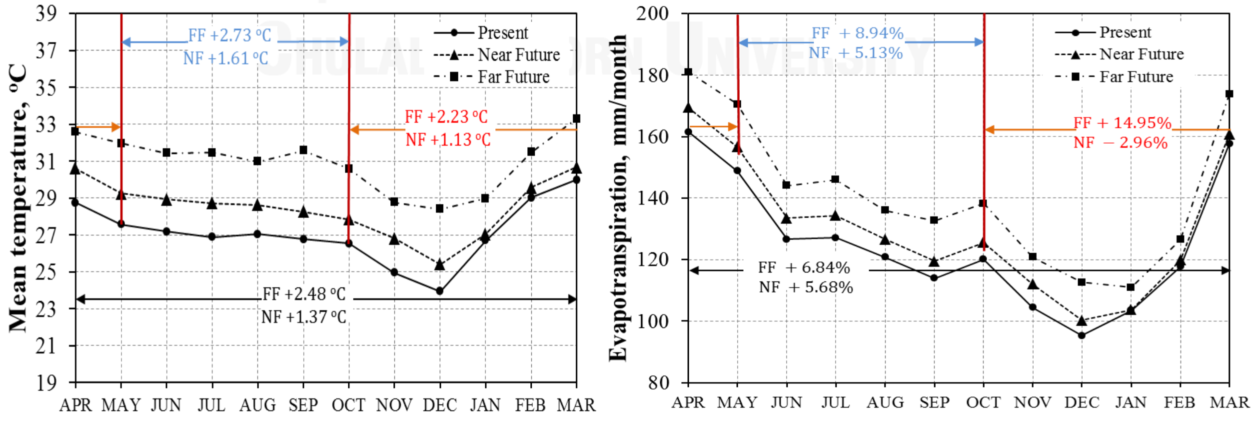
B.1 The change on climate and rainfall

B.1.1 The change on climate

The change of climate in the concerned area was used to estimate the irrigation water demand in Lower Chao Phraya Basin. The change of climate in Lower Chao Phraya Basin was evaluated in near and far future period. The climate included maximum, minimum, mean and evapotranspiration. The monthly mean climate in the Lower Chao Phraya Basin was compared in present, near and far future period as shown in Figure B.1.



(a) Maximum temperature (b) Minimum temperature



(c) Mean temperature (d) Evapotranspiration

Figure B.1 The monthly mean climate in Lower Chao Phraya Basin

B.1.2 The change on rainfall

The change of rainfall in the concerned area include Yom River Basin, Wang River basin, Upper Ping River Basin, Lower Ping River Basin, Sakaekang River Basin ,and Lower and Upper Chao Phraya River Basin. The change of rainfall in the concerned area was evaluated in near and far future period. The monthly mean rainfall in the concerned area was compared in present, near and far future periods as shown in Figure B.1 to B.6.

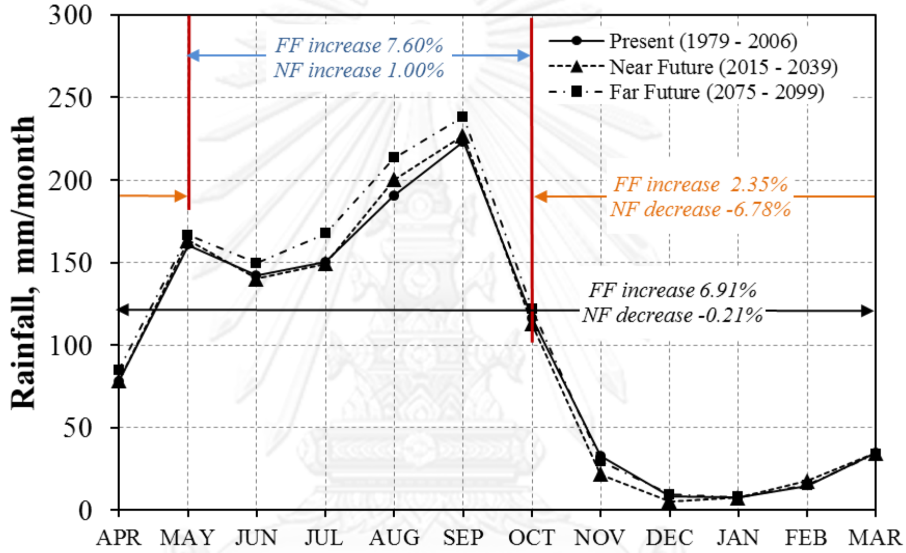


Figure B.2 The monthly mean rainfall in Yom River Basin

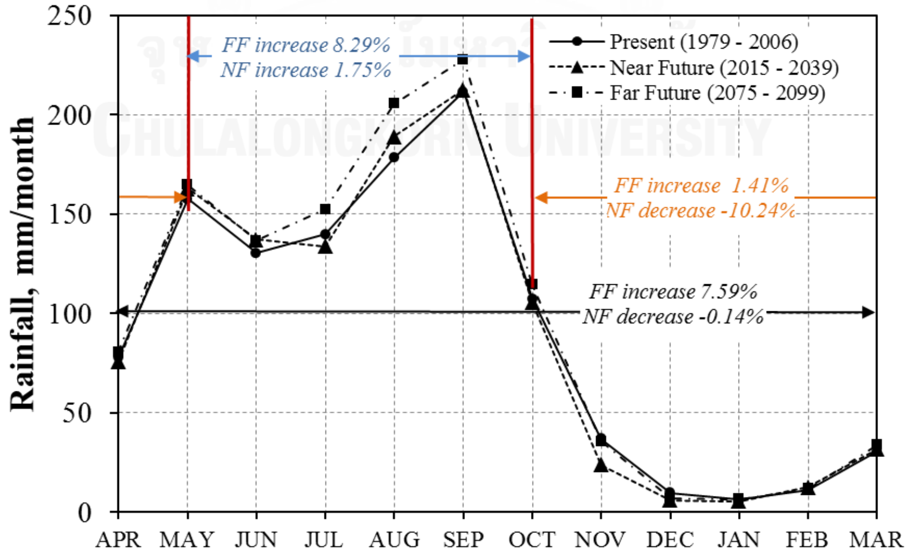


Figure B.3 The monthly mean rainfall in Wang River Basin

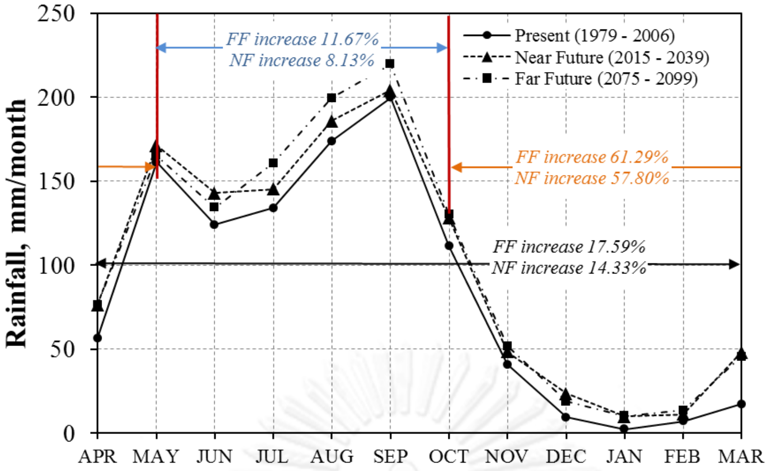


Figure B.4 The monthly mean rainfall in Upper Ping River Basin

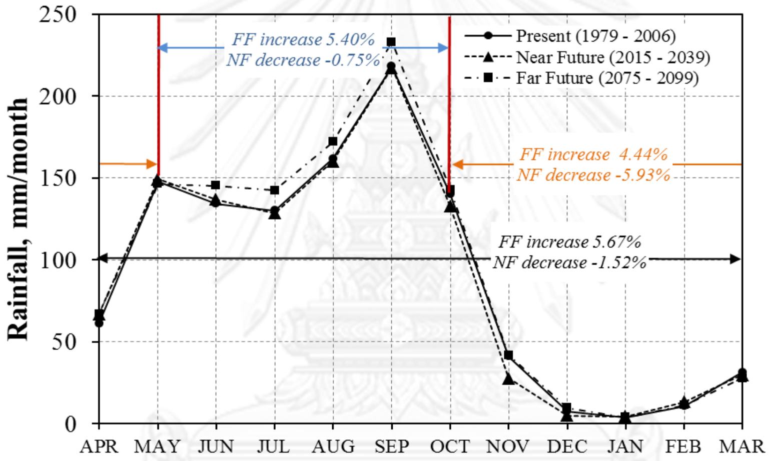


Figure B.5 The monthly mean rainfall in Lower Ping River Basin

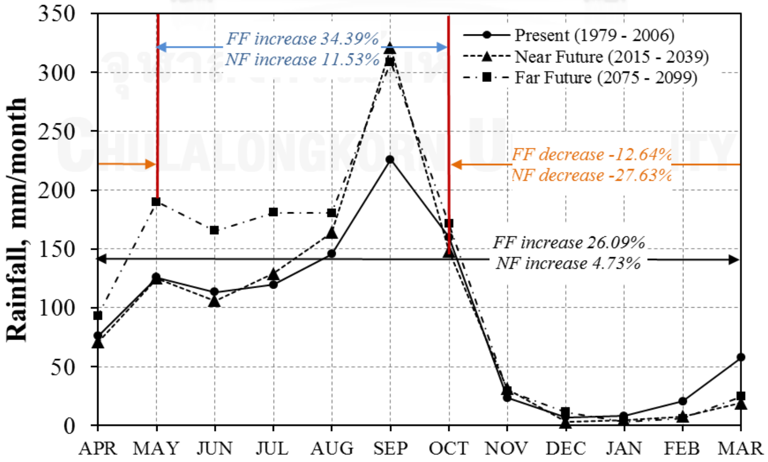


Figure B.6 The monthly mean rainfall in Lower Chao Phraya River Basin

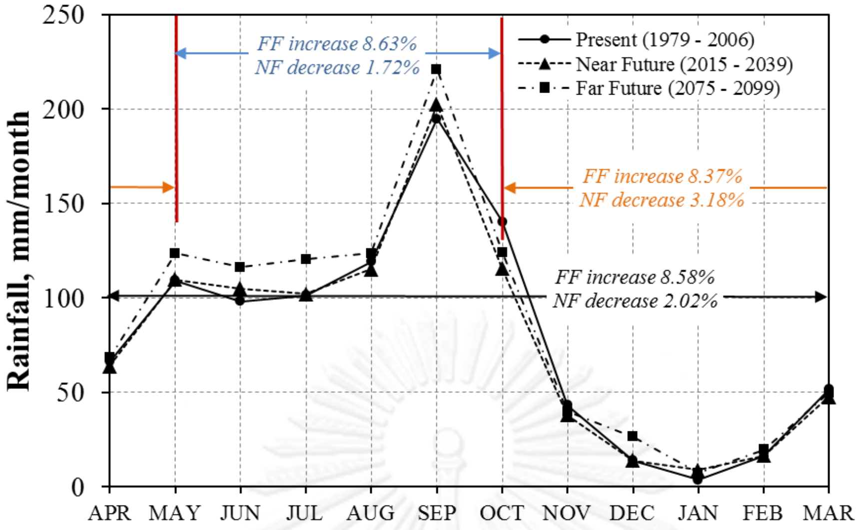


Figure B.7 The monthly mean rainfall in Upper Chao Phraya River Basin

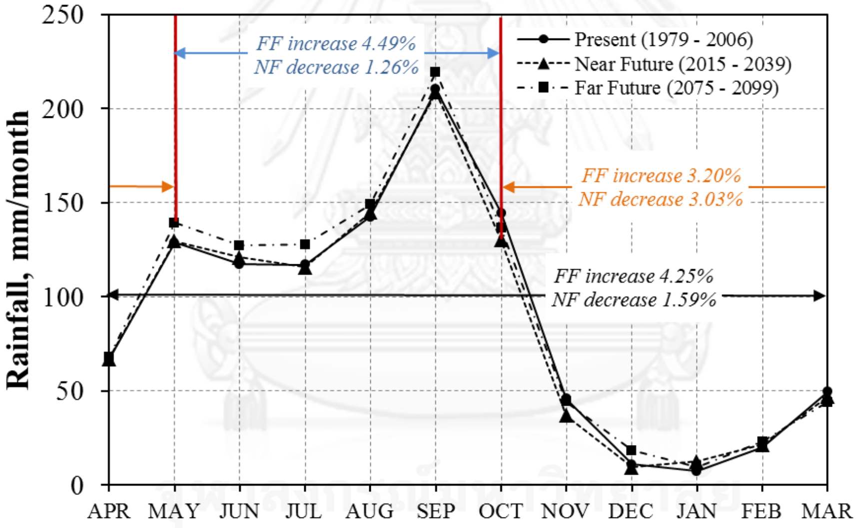


Figure B.8 The monthly mean rainfall in Sakaekang River Basin

B.2 The change on lateral flow

The change of runoff in the concerned area includes Yom River Basin, Wang River basin, Upper Ping River Basin, Lower Ping River Basin, Sakaekang River Basin ,and Lower and Upper Chao Phraya River Basin. The change of lateral flow in the concerned area was evaluated in near and far future period. The monthly mean runoff in the concerned area was compared in present, near and far future periods as shown in Figure B.7 to B.10.

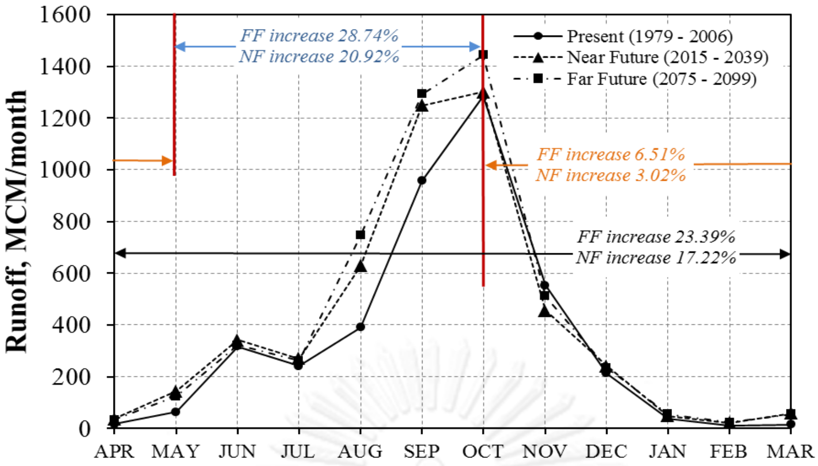


Figure B.9 The monthly mean runoff in Yom River Basin

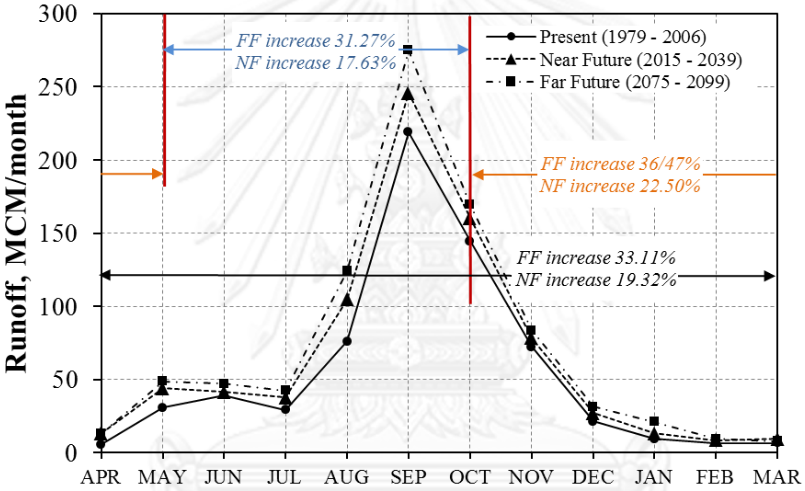


Figure B.10 The monthly mean runoff in Wang River Basin

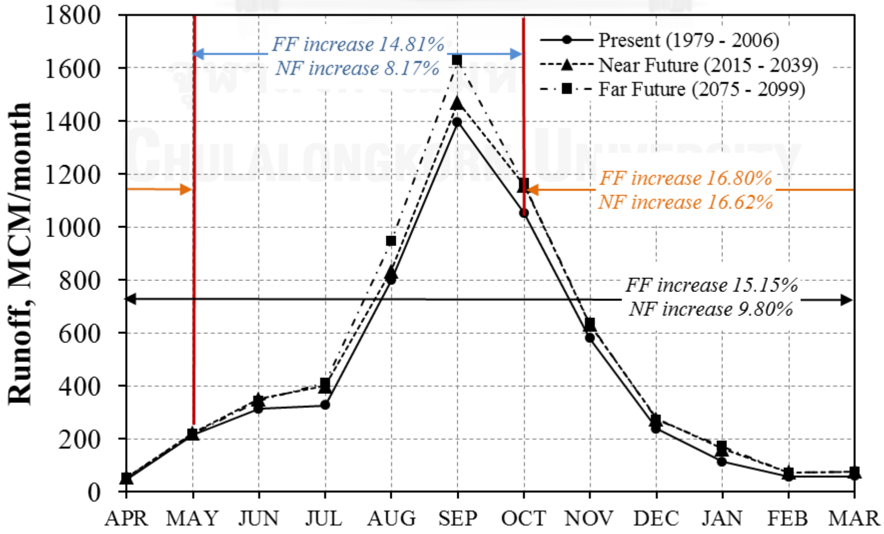


Figure B.11 The monthly mean runoff in Upper Ping River Basin

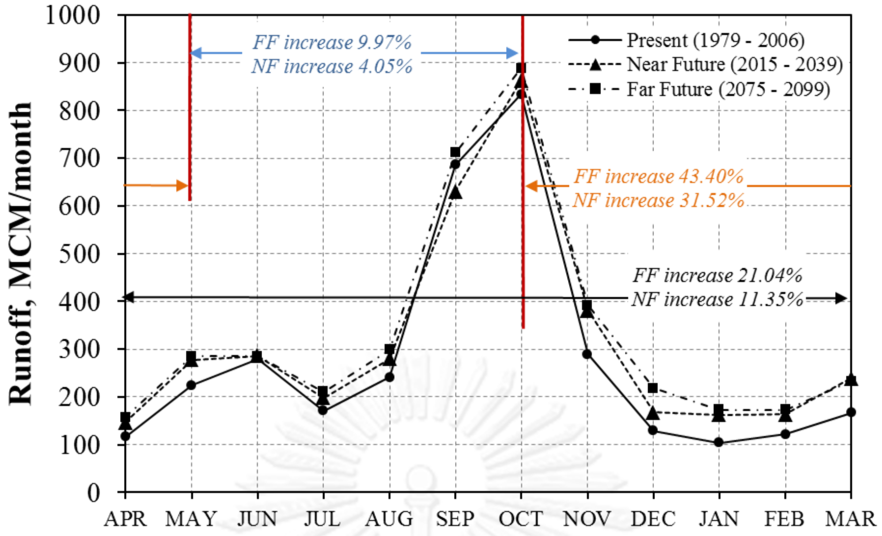


Figure B.12 The monthly mean runoff in Lower Ping River Basin

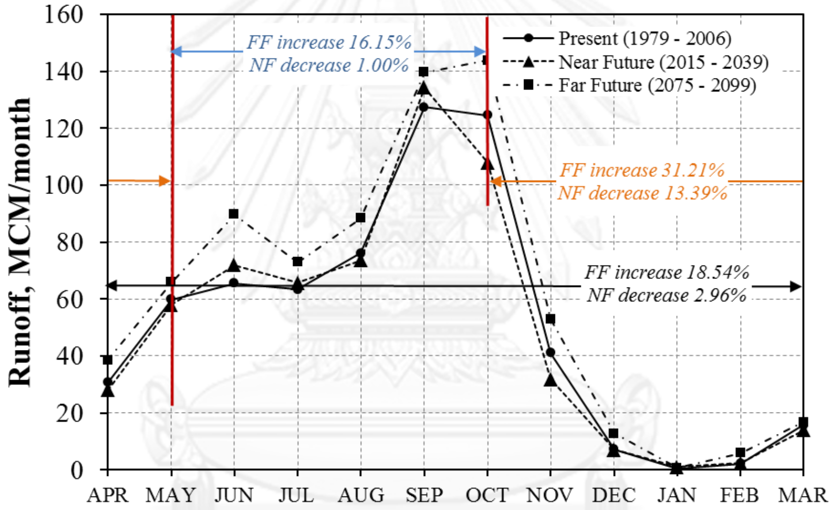


Figure B.13 The monthly mean runoff in Upper Chao Phraya

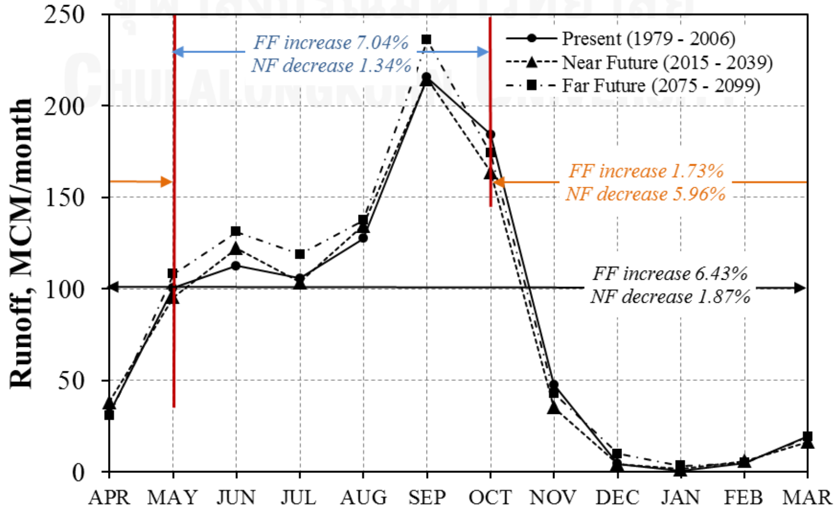


Figure B.14 The monthly mean runoff in Sakaekang River Basin

B.3 Runoff estimation

B.3.1 Rainfall-Runoff Process

This study used HEC-HMS rainfall-runoff model that developed by the Hydrologic Engineering Centre of US Army Corps of Engineers. This model is a semi-distributed conceptual model for catchment modeling. The model simulates the precipitation-runoff and routing processes. A typical HEC-HMS representation of catchment runoff process is shown in Figure B.11. To represent the different components of the runoff process, HEC-HMS use different models including:

- Model that compute runoff volume.
- Model of direct runoff (overland flow and interflow).
- Model of base flow.
- Model of channel flow (routing model).

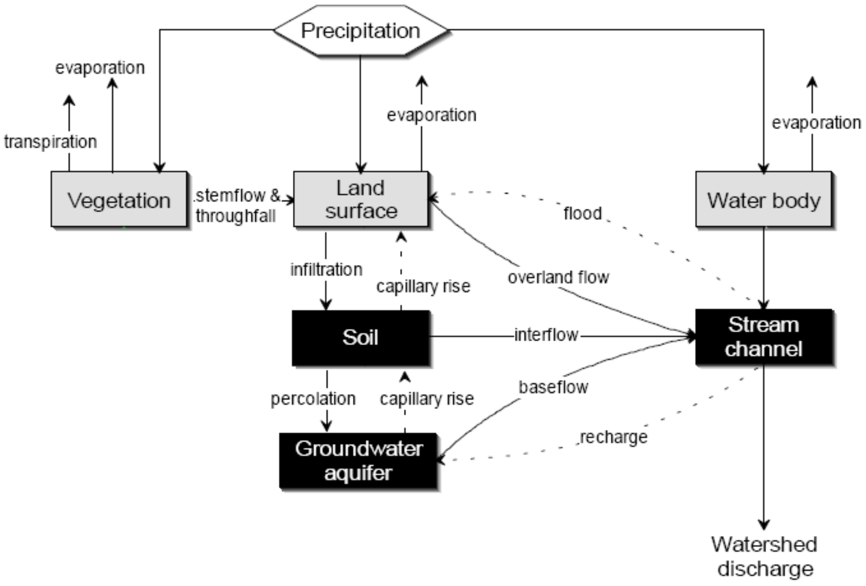


Figure B.11 Systems diagram of the runoff process at local scale (after Ward, 1975)

1) Model that compute runoff volume

The Soil Conservation Service (SCS) Curve Number (CN) model estimates precipitation excess as a function of cumulative precipitation, soil cover, land use, and antecedent moisture, using the following equation:

$$P_e = \frac{(P-I_a)^2}{P-I_a+S} \qquad (1)$$

where P_e is accumulated precipitation excess at time t; P is accumulated rainfall depth at time t; I_a is the initial abstraction (initial loss); and S is potential maximum retention, a measure of the ability of a watershed to abstract and retain storm precipitation.

Until the accumulated rainfall exceeds the initial abstraction, the precipitation excess, and hence the runoff, will be zero. From analysis of results from many small experimental watersheds, the SCS developed an empirical relationship of I_a and S:

$$I_a = 0.2\,S \qquad (2)$$

Therefore, the cumulative excess at time t is:

$$P_e = \frac{(P-0.2S)^2}{P+0.8S} \qquad (3)$$

Incremental excess for a time interval is computed as the difference between the accumulated excess at the end of and beginning of the period.

The maximum retention, S, and watershed characteristics are related through an intermediate parameter, the curve number (commonly abbreviated CN) as:

$$S = \frac{25400-254CN}{CN} \quad \text{(SI)} \qquad (4)$$

where CN values range from 100 (for water bodies) to approximately 30 for permeable soils with high infiltration rates.

2) Model of direct runoff

Clark's unit hydrograph (UH) method is used for the transformation of excess precipitation (runoff volume) to runoff. This method explicitly represents two critical process of transformation:

- Translation or movement of the excess from its origin throughout the drainage to the watershed outlet; and
- Attenuation or reduction of the magnitude of the discharge as the excess is stored throughout the watershed.

The transformation is defined in the model by two parameters: time of concentration, tc, and the storage coefficient, R. The basin storage coefficient, R, is an index of the temporary storage of precipitation excess in the catchment as it drains to the outlet. It can be estimated via calibration if gaged precipitation and streamflow data are available. Though R has units of time, there is only a qualitative meaning for it in the physical sense. Clark (1945) indicated that R can be computed as the flow at the inflection point on the falling limb of the hydrograph divided by the time derivative of flow.

3) Model of base flow

Monthly constant method is used for applying base flow estimation which formulates from the relationship between the previous monthly rainfall and base flow for wet season (April to October) follows as this equation:

$$Q_B = aR_{t-1} + C \tag{5}$$

where Q_B is the baseflow or minimum runoff in present month, m^3/sec, R_{t-1} is the antecedent rainfall amount, mm/month , C is the constant value.

For dry season, the monthly baseflow could be calculated from the relationship between the antecedent rainfall amount and minimum runoff in previous month and minimum runoff in present month. The equation follows as:

$$Q_B = aR_{t-1} + bQ_{Bt-1} + C \tag{6}$$

where Q_B is the baseflow or minimum runoff in present month, m^3/sec, Q_{Bt-1} is the minimum runoff in previous month, m^3/sec, R_{t-1} is the antecedent rainfall amount, mm/month, C is the constant value.

4) Model of channel flow

The Muskingum method is used for the flow routing. This method is a commonly used hydrological routing method for handling a variable discharge-storage relationship (Chow et al., 1988). It uses a simple finite difference approximation of the continuity equation:

$$\frac{I_{t-1}+I_t}{2} - \frac{O_{t-1}+O_t}{2} = \frac{S_t-S_{t-1}}{\Delta t} \tag{7}$$

where I_{t-1} and I_t are the inflow hydrograph ordinates at times t-1 and t, m^3/sec, respectively, O_{t-1} and O_t are the outflow hydrograph ordinates at times t-1 and t, m^3/sec, respectively, S_{t-1} and S_t are the storage in the reach at times t-1 and t, m^3 respectively;

The storage is modeled as the sum of prism and wedge storage. The prism storage is the volume defined by the water surface profile at steady stage, while the wedge storage is the additional volume under the profile of the flood wave. The storage at time t, S_t, is defined as:

$$S_t = KO_t + KX(I_t - O_t) = K[XI_t + (1 - X)O_t] \tag{8}$$

where K is travel time of the flood wave through routing reach; and X is dimensionless weight ($0 \leq X \leq 0.5$)

From Equations (7) and (8), it follows that

$$O_t = \left(\frac{\Delta t - 2KX}{2K(1-X)+\Delta t}\right) I_t + \left(\frac{\Delta t + 2KX}{2K(1-X)+\Delta t}\right) I_{t-1} + \left(\frac{2K(1-X)-\Delta t}{2K(1-X)+\Delta t}\right) O_{t-1} \tag{9}$$

The Muskingum method is used for the flow routing. This method is a commonly used hydrological routing method for handling a variable discharge-storage relationship (Chow et al., 1988). The Muskingum Routing method was selected to model stream routing. Assumptions include a Muskingum X value of 0.1 (indicating a small, natural stream), a subreach value of 2, and a streamflow speed of 3.0 km/hr was used to calculate Muskingum K value (length of time to travel a stream reach).

B.3.2 The univariate gradient optimization method

The univariate gradient optimization technique was adopted to optimize the suitable runoff parameters. Then, the algorithm evaluates the last adjustment for all parameters to identify the parameter for which the adjustment yielded the greatest reduction in the objective function. That parameter is adjusted, using the procedure defined here. This process continues until additional adjustments will not decrease the objective function by at least 1% (USACE, 2000). The objective function is sum square residual function that minimize sum square residual matching with the optimize value for each parameter.

The calibrated runoff parameter included initial abstraction (Int) and Curve number (CN). Sum of squared residuals (Diskin and Simon, 1977). This is a commonly-used objective function for model calibration. It compares all ordinates, but uses the squared differences as the measure of fit. Squaring the differences also treats overestimates and underestimates as undesirable. This function is implicitly a measure of the comparison of the magnitudes of the peaks, volumes, and times of peak of the two hydrographs. (USACE, 2000)

$$Z = \sum_{i=1}^{NQ} [q_0(i) - q_s(i)]^2 \qquad (10)$$

where Z is objective function; NQ is number of computed hydrograph ordinates; $q_o(i)$ is the observed flows; $q_s(i)$ is calculated flows, computed with a selected set of model parameters.

B.3.3 Parameter estimation procedures

The univariate gradient method was adopted to optimize the rainfall-runoff parameters included the initial abstraction (Int), Curve number (CN) Storage Clark number (Sc). This optimization technique was used to optimize the parameter of runoff volume. The processes of the optimization will be attempted to adjust the optimum value of each parameter. The steps of parameter optimization in HEC-HMS rainfall-runoff model follow as:

1) Select the optimization method, the univariate gradient was used to apply in this study.

2) Select the objective function, the sum square residual was used to apply in this study.

3) Define the location or the considering junction.

4) Define the percentage of missing flow (%).

5) Define the start and end date and time.

6) Select the parameter which desire to optimize and set up the initial value.

7) Set up the range of optimizing value as minimum and maximum value.

B.3.4 Specification of rainfall patterns

The specification of rainfall pattern is the process which defines the type of rainfall pattern in each year. The procedures for specifying the rainfall pattern follow as:

1) Calculate the accumulative rainfall at the end of each month in April to October.

2) Find out the slope of the accumulative rainfall in each month by taking the accumulative rainfall divided by the accumulative days at the end of the month.

3) Transform the slope of accumulative rainfall to anomaly rainfall followed as this equation:

$$S' = \frac{S-\mu}{\sigma} \tag{11}$$

Where S' is the anomaly accumulative rainfall; S is the accumulative slope; μ is the mean of accumulative slope and σ is the standard deviation of accumulative slope.

4) Define the monthly rainfall intensity by classifying the anomaly slope into 3 levels follow as:

- High intensity is the anomaly slope over than σ/2 of anomaly slope.
- Medium intensity is the anomaly slope between σ/2 and –σ/2 of anomaly slope.
- Low intensity is the anomaly slope under than –σ/2 of anomaly slope.

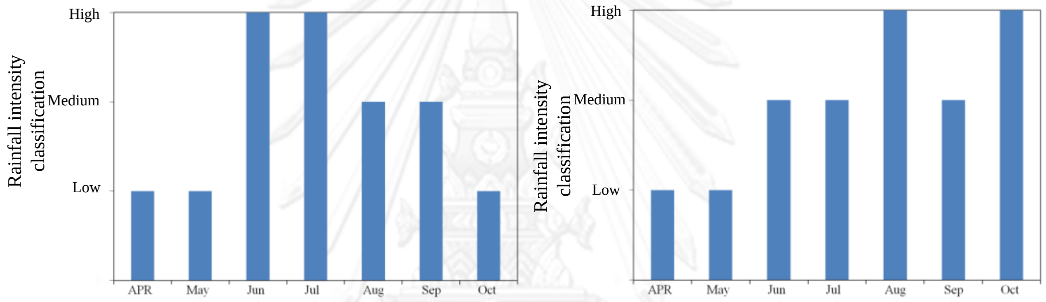
5) Define the rainfall intensity in each month by the classification of rainfall intensity from step 4 in April to October.

6) Classify the anomaly slope level into the rainfall pattern into 5 Types follow as:

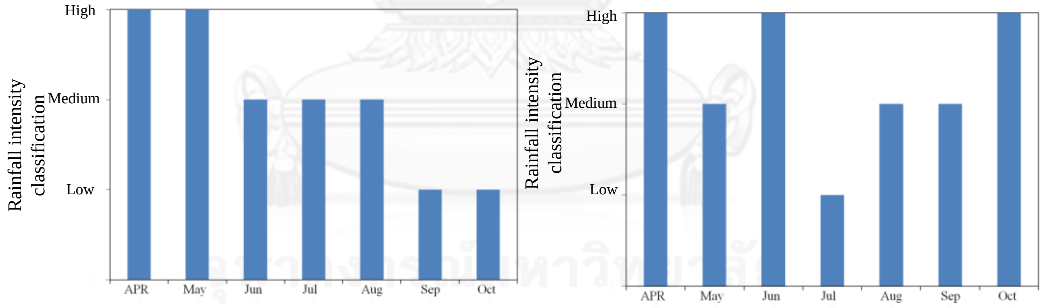
- Type 1 is the high intensity at the mid of rainy season (high intensity in June and July or August and September)
- Type 2 is the high intensity at the end of rainy season (high intensity in August to October)

- Type 3 is the high intensity at the early rainy season (high intensity in April to May)
- Type 4 is the high intensity at the early rainy season and the end of rainy season. (High intensity in April to May and August to October)
- Type 5 is the low intensity at the early rainy season and the end of rainy season. (low intensity in April to May, July to August and October.

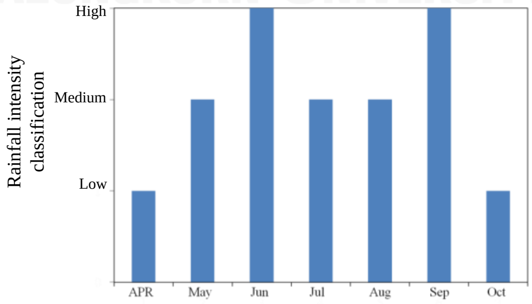
The example type of rainfall pattern and monthly rainfall intensity slope show as Figure B.12 and B.13, respectively.



(a) Type 1 (b) Type 2



(c) Type 3 (d) Type 4



(5) Type 5

Figure B.12 The example type of rainfall pattern

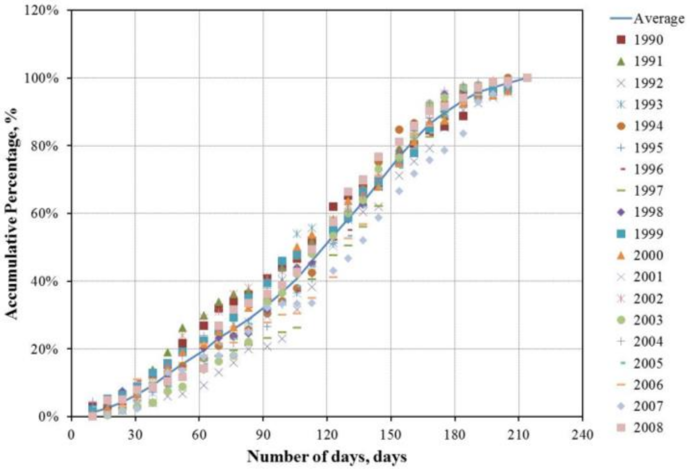


Figure B.13 The example of monthly rainfall intensity slope

B.3.5 Model configuration

The rainfall-runoff model is set up according to the flow direction and the characteristic of sub basin such as the watershed area and stream length. The flowchart of the river basin network was formulated as Figure B-14. The boundary of each sub basins can be generated by using the digital elevation map (DEM). The calibrated runoff stations included N.1 Nan at the forestry office, Nan, N.13A Nan at the highway bridge (Ban Bun Nak), Nan, Inflow of Sirikit Dam , N.12A Nan at Ban Hat Phai, Uttaradit, N.60 Nan at Ban Hat song Khwae, Uttaradit and N.5A Nan at Ban Goey Chai, Nakornsawan.

However this hydrological model cannot involve the reservoir operation to simulate the completely runoff of Nan River Basin. This model considers the historical release of Sirikit as the input variables for the downstream runoff simulation. This partial runoff simulation can provide the inflow of Sirikit Dam and the lateral flow of the downstream sub basins for studying reservoir operation. The model configuration follows as:

1) Input variables preparation

1.1) Observed rainfall is averaged into each sub basin the thiessen polygon method.

1.2) Observed runoff is entered into the rainfall-runoff model for the parameter optimization.

1.3) Bias corrected rainfall in the present (1979 – 2006), near future (2015 – 2039) and far future (2075 – 2099).

1.4) Release of Sirikit Dam in year 1979 – 2008

2) Input parameters preparation

Initial abstraction (Int) was initiated to set up from the antecedent rainfall. (previous 1 month rainfall).

Curve number (CN) was initiated to set up by the characteristic of the soil group and the cover complex in each sub basins. (see McChen,2004, p.159-162) Hence, the cover complex was estimated from the land use classification. While the soil group was defined from the soil classification map, that retrieved from LDD. The initial curve number show as Table C.1.

Time of concentration (tc) follows as:

$$\mathrm{t}_c = \frac{[0.827 \times A^{0.2} \times 24]}{2} \tag{12}$$

where t_c is the time of concentration, hours; A is the watershed area, Km^2

Storage coefficient (S_c) follows as: (Russell, Kenning, and Sunnell, 1979)

$$\mathrm{S}_c = c \times t_c \tag{13}$$

where t_c is the time of concentration, hours, c is a calibration parameter that, depending on the use of the soil, takes the following values: densely forested area 8 – 12 ,predominantly agricultural area 1.5 – 2.8, towns 1.1 – 2.1.

Muskingum X value was initiated to set up equal to 0.2.

Muskingum K value was calculated by the length of stream divide stream flow speed that was assumed as 3.0 Km/hr. (Kawasaki et al., 2010)

3) Model simulation periods

3.1) Model calibration period is year 1990 – 2008.

3.2) Model re-sumulation for parameter function verification is year 1990 – 2008.

3.3) Model validation period is year 1979 – 1989.

3.4) Runoff simulation for the impact assessment is year 1979 – 2006, year 2015 – 2039 and year 2075 – 2099.

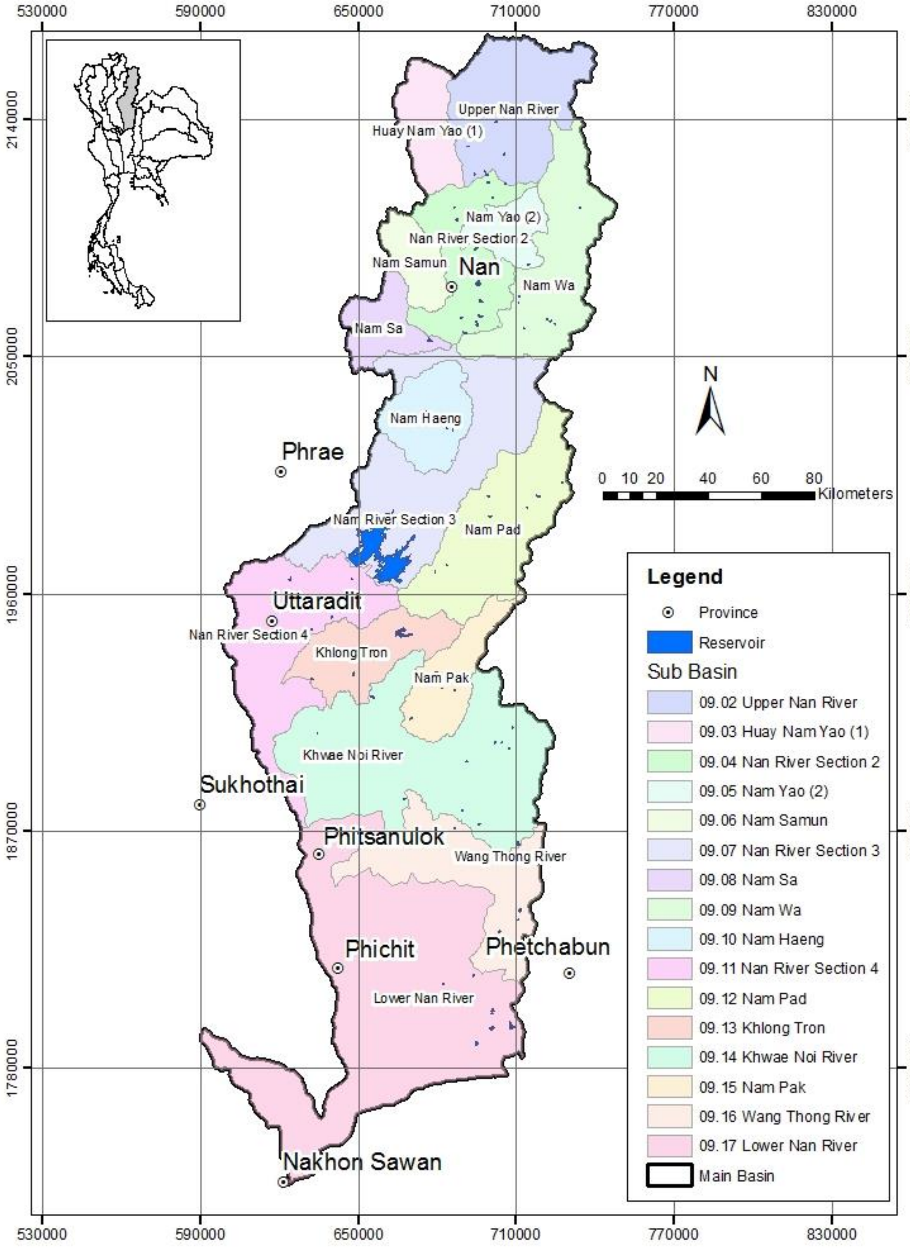


Figure B.14 The sub basin of Nan River Basin

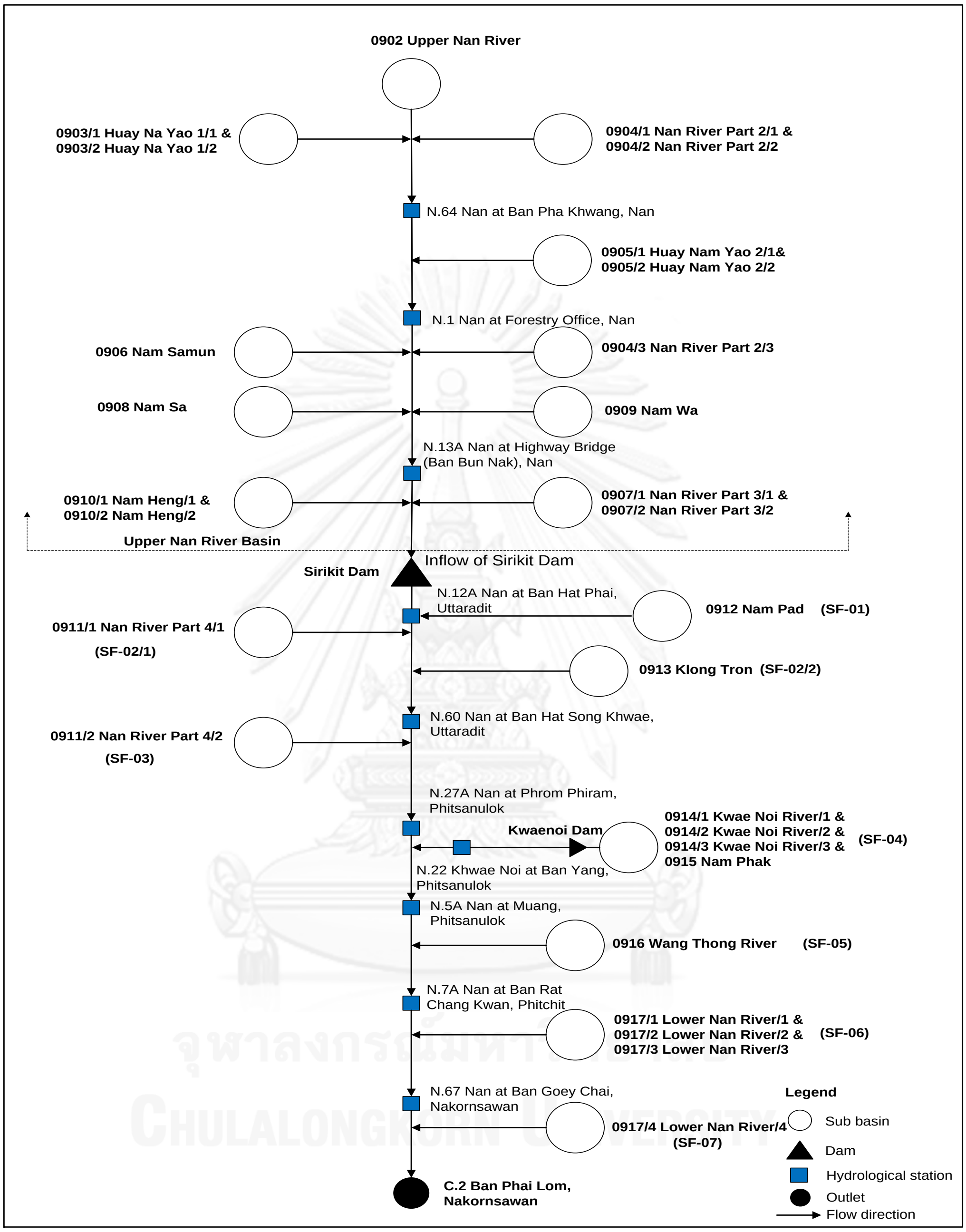


Figure B.15 The flowchart of the river basin network

B.3.6 Rainfall-runoff model calibration

The rainfall-runoff model was calibrated by running the HEC-HMS rainfall-runoff model in year 1990 – 2007. The runoff was simulated in each year based on daily observed rainfall data basis. The modeling period was run separating into 2 seasons, i.e. wet and dry season. The wet season part would run before dry season in each year due to the baseflow estimation from the previous monthly rainfall and previous monthly baseflow. (show in Eq.22 in Chapter 4) .The purpose of the model simulation is to estimate the parameter functions according to the rainfall patterns. However the univariate gradient optimization method was used to find the optimum parameters in each year. (The goodness of fit test in each year is shown as Table C.17.) The goodness of fit indices of the integrated results whole the calibration period shows in Table B.1.

Table B.1 The goodness of fit indices for model calibration

	Inflow	N.12A	N.60	N.5A	N.24	N.1	N.13A
%Diff of Volume	14.01	4.14	6.30	0.08	-38.80	10.42	5.15
R	0.85	0.92	0.77	0.93	0.78	0.87	0.86
R^2	0.73	0.85	0.61	0.87	0.61	0.76	0.75
RMSE	131.93	50.92	83.52	59.84	36.22	76.43	174.60
SE	116.46	37.52	56.47	52.31	12.13	61.21	114.69
Efficiency of Nash	0.63	0.80	0.51	0.81	0.41	0.68	0.67

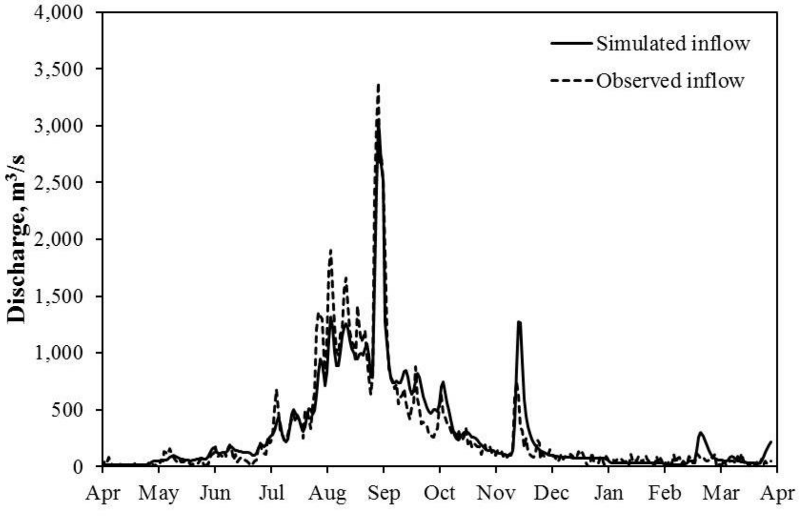


Figure B.16 Observed and simulated inflow of Sirikit Dam in year 1995

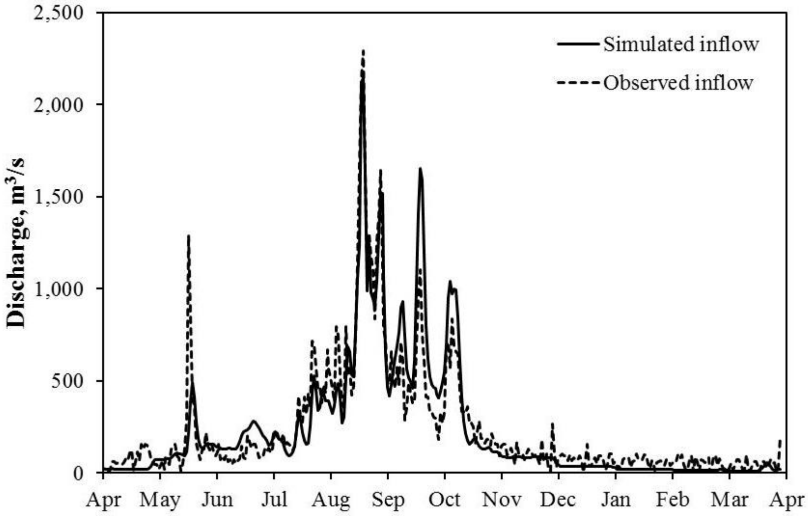


Figure B.17 Observed and simulated inflow of Sirikit Dam in year 2006

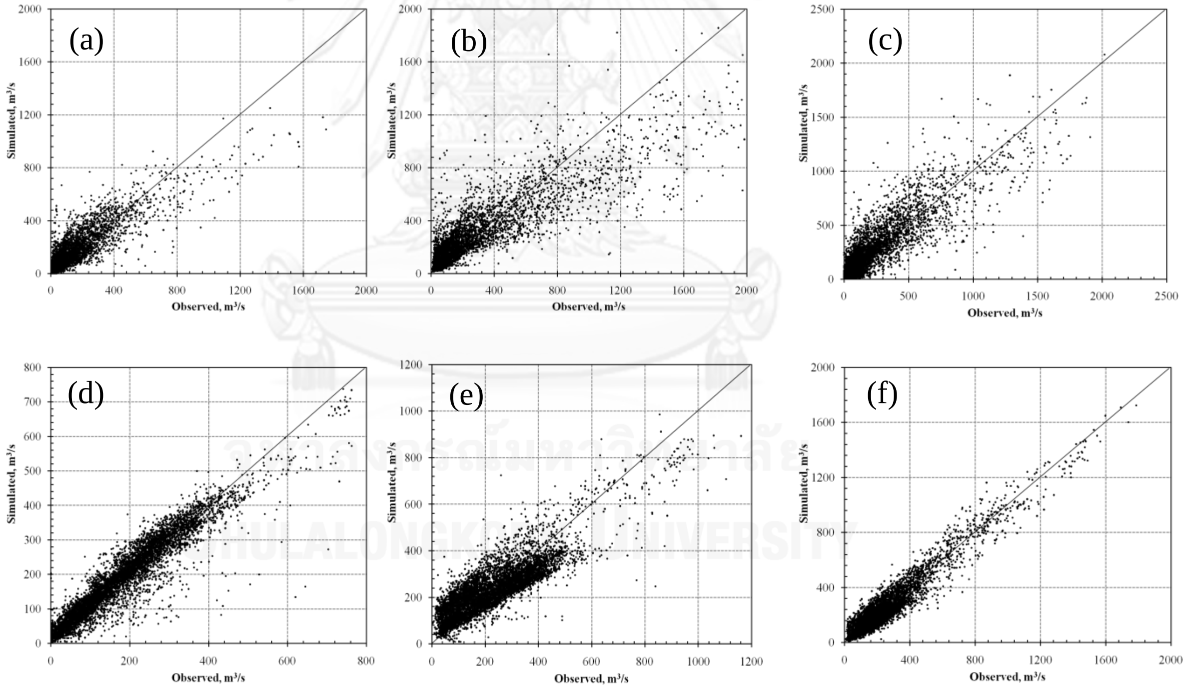


Figure B.18 Relationships between observed and simulated data in Nan River Basin over the period 1990 – 2007 at (a) N.1, (b) N.13A, (c) Inflow, (d) N.12A, (e) N.60, and (f) N.5A

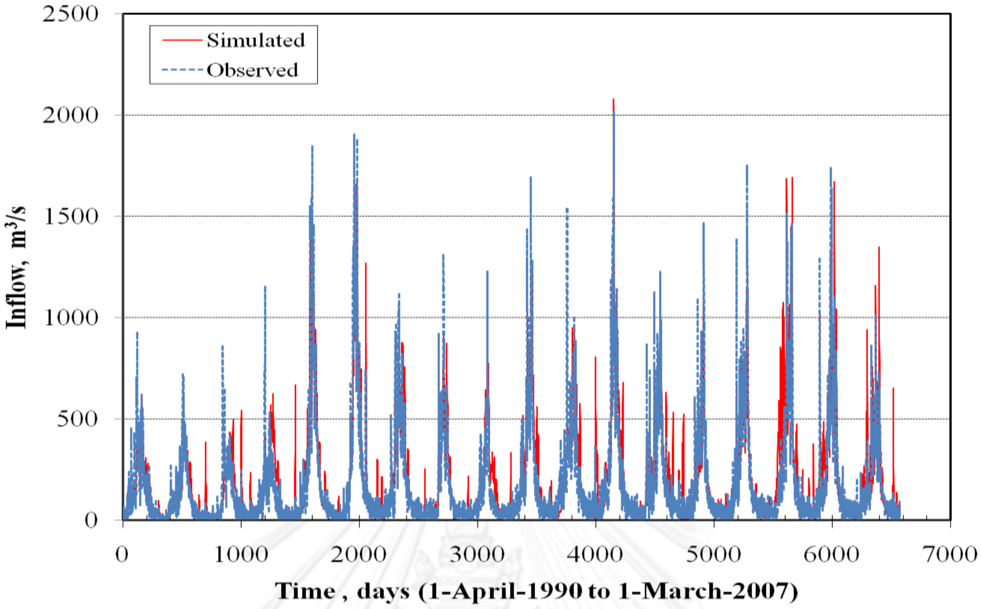


Figure B.19 Observed and simulated inflow of Sirikit dam in year 1990 to 2007

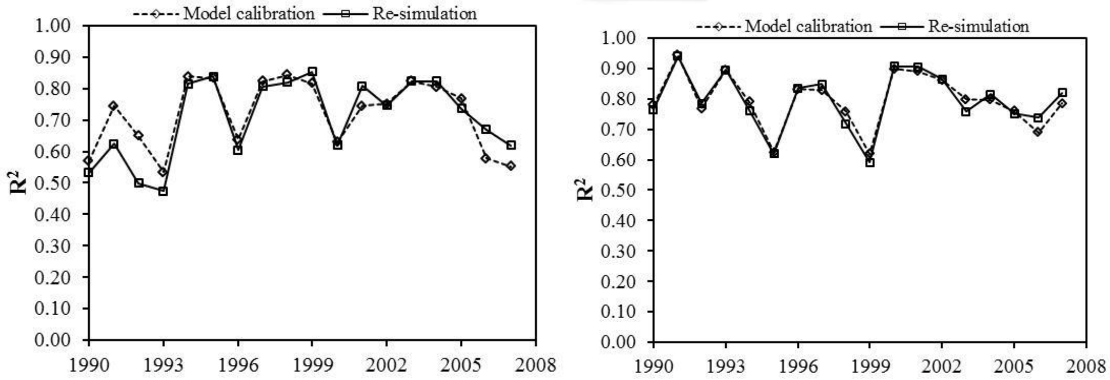
B.3.7 Parameter functions analysis

The runoff parameter functions were derived from the parameter optimization in the model calibration stage. Due to the monthly rainfall in year 1990 – 2006 (17 years) varied in the different pattern. Again the 5 rainfall patterns which was mentioned in the rainfall patternization procedures, the parameter functions could be formulated according to the monthly rainfall pattern. The parameter functions of the sub basin that included initial abstraction (Int), curve number (CN) and storage coefficient (Sc) show as Table C.2. The goodness of fit for the re-simulated process show as Table B.3.

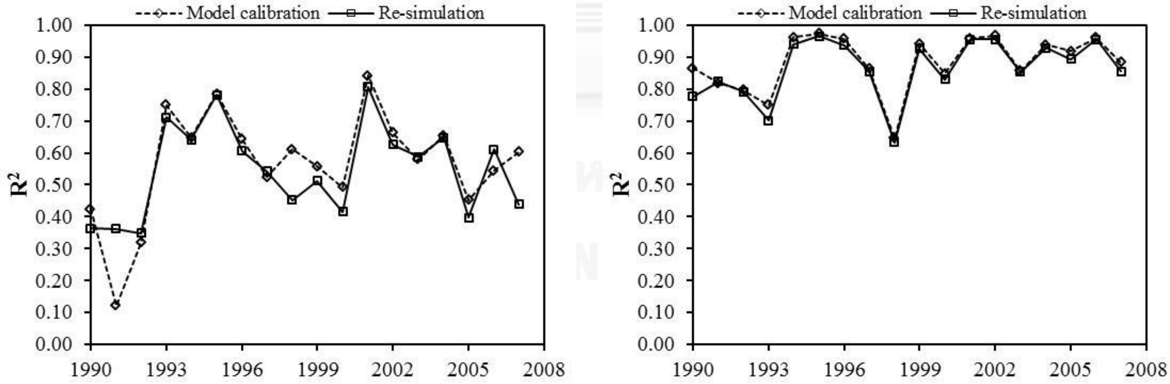
The runoff parameter functions were verified by re-simulating the runoff to evaluate the efficiency of the parameters. The comparison of the correlation (R^2), the root mean square error (RMSE) and the Efficiency of Nash between the model calibration and model re-simulation show as Figure B.20 to B.22, respectively. The results show the model re-simulation give good fit indices corresponding to model calibration.

Table B.2 The goodness of fit indices for the re-simulated process

Goodness of fit indices	Inflow	N.12A	N.60	N.5A	N.24	N.1	N.13A
%Diff of Volume	19.78	4.02	4.45	-0.02	-21.07	10.70	8.92
R	0.86	0.92	0.78	0.94	0.81	0.88	0.87
R^2	0.74	0.85	0.63	0.88	0.66	0.79	0.77
RMSE	134.78	50.99	83.10	53.45	31.68	73.56	173.35
SE	121.08	37.71	53.25	48.64	14.80	60.03	116.47
Efficiency of Nash	0.59	0.81	0.50	0.85	0.55	0.67	0.63

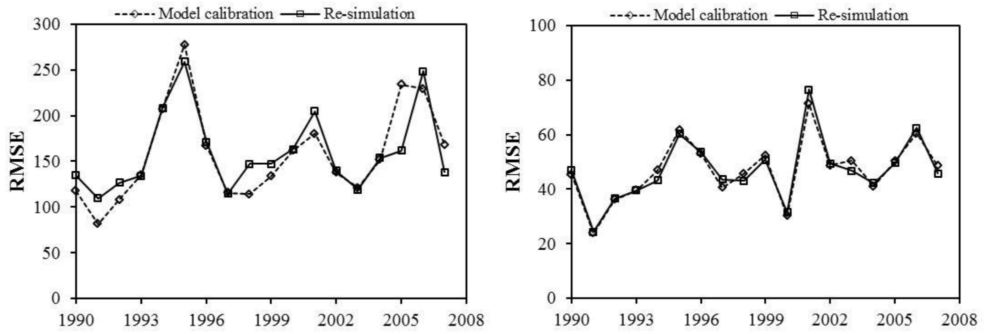


(a) Inflow of Sirikit Dam (b) N.12A

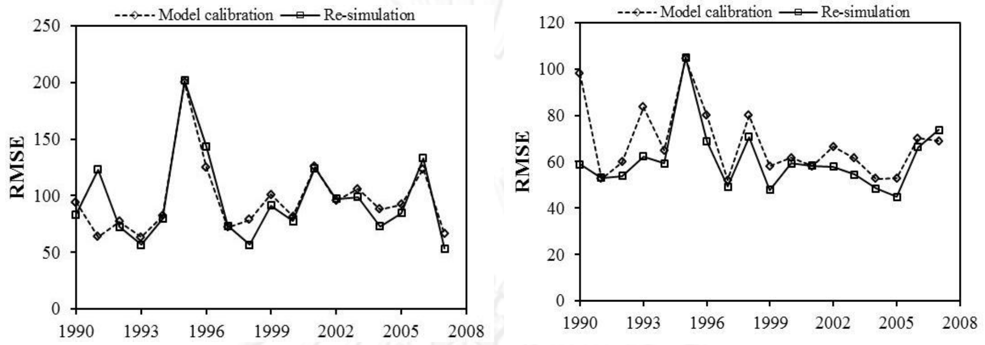


(c) N.60 (d) N.5A

Figure B.20 The comparison of the correlation (R^2) between the model calibration and re-simulation

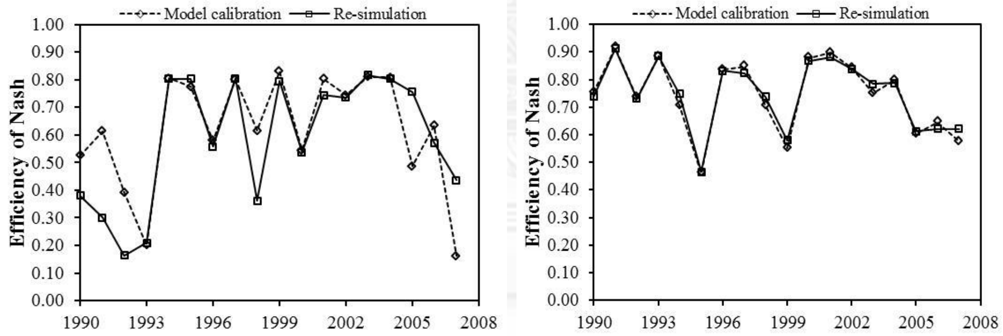


(a) Inflow of Sirikit Dam (b) N.12A

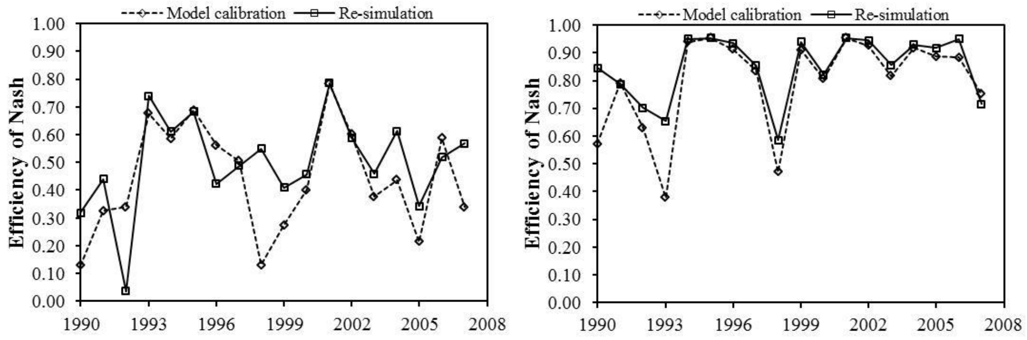


(c) N.60 (d) N.5A

Figure B.21 The comparison of the RMSE between the calibration and re-simulation



(a) Inflow of Sirikit Dam (b) N.12A



(c) N.60 (d) N.5A

Figure B.22 The comparison of the efficiency of Nash between the calibration and re-simulation

B.3.8 Model validation

Due to the mostly observed runoff data in the runoff gauge stations was recorded only in year 1990 – 2006. However the available observed runoff which has the longer time series is the inflow of Sirikit Dam, the recorded data started from 1975 – present. So the model validation stage would simulate the runoff in year 1979 – 1989, and then compared the simulated runoff result with the observed inflow of Sirikit Dam. The comparison of the goodness of fit indices of the model validation show as Table B.3. The comparison between the observed and simulated inflow show as Figure B.23. For a given initial abstraction (Int), CN value, storage coefficient (Sc) and base flow were calculated for each event with the external process, and then combined as a continuous time-series data to conduct a continuous simulation in HEC-HMS.

Table B.3 The comparison of the goodness of fit indices for validation process

Goodness of fit indices	Inflow
%Diff of Volume	15.68
R	0.90
R^2	0.82
RMSE	87.74
SE	82.38
Efficiency of Nash	0.79

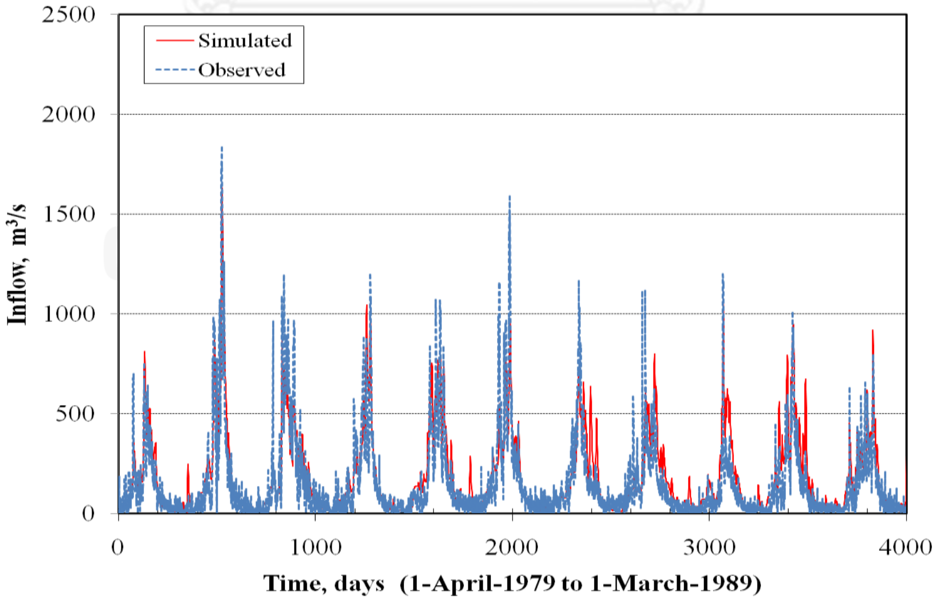


Figure B.23 Observed and simulated inflow of Sirikit dam in year 1979 to 1989

B.4 The lateral flow of the concerned area estimation

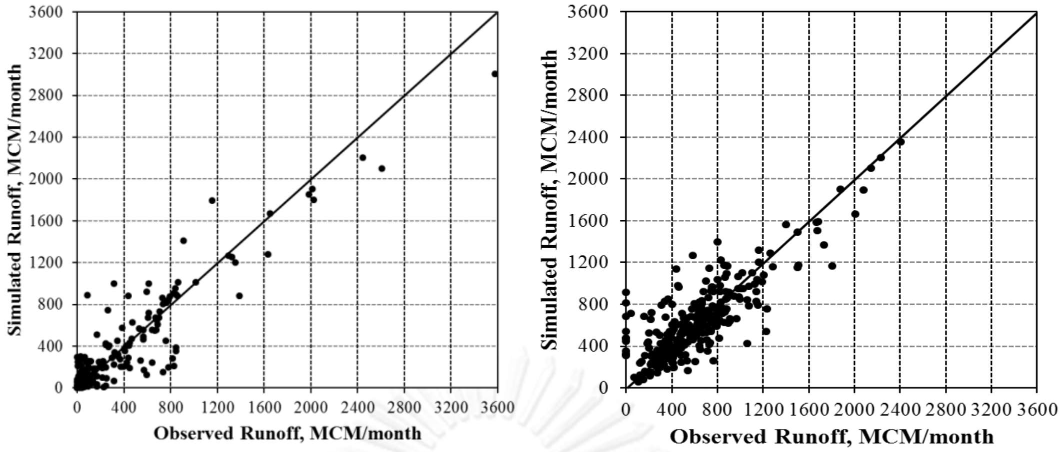
The lateral flow of the concerned area was estimated by adopting from the previous study and the multiple regression method. The runoff of concerned area which used the results from the previous study included the Yom River Basin, Ping River Basin, and Wang River Basin. Regarding these previous study, the runoff estimation was used HEC-HMS rainfall-runoff model as the tool for the runoff simulation. On the other hand, The runoff of concerned area which used the results from the multiple regression method included the Upper Chao Phraya River Basin and Sakaekang River Basin. This multiple regression was formulated the rainfall-runoff relationship equations based on the daily basin. However this study was checked the accuracy from the results from both sources as follow:

B.4.1 The runoff of concerned area validation

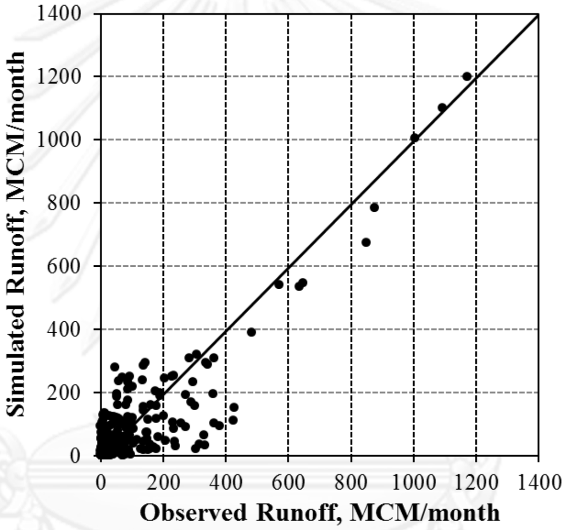
The runoff of concerned area was focused in the Yom River Basin, Ping River Basin, and Wang River Basin. The observed runoff station which used to validate the runoff simulating results including Y.17, P.17 and W.4A. It was checked the accuracy by using the goodness of fit test including the correlation of determination (R^2), root mean square error (RMSE) and standard error (SE). The estimated runoff was compared with the observed runoff shown in Table B.4 and Figure B.24.

Table B.4 The comparison of the goodness of fit indices

Station	R^2	RMSE	SE
Y.17	0.86	184.87	185.55
P.17	0.69	222.93	221.12
W.4A	0.78	67.01	66.81



(a) Y.17 (b) P.17



(c) W.4A

Figure B.24 Relationships between observed and simulated data in Y.17, P.17 and W.4A

B.4.2 The lateral flow estimation by multiple regression method

The lateral flow of the Sakaekang and Upper Chao Phraya River basin was formulated from the relationship between the daily rainfall and runoff using the multiple linear regressions. In the lateral flow of Sakaekang River Basin, the oberserved runoff station Ct.8 was selected from the station which would not disturbed from the backwater effect from Chao Phraya River. The rainfall and runoff data in 2009 – 2012 was used to formulate the equation. The correlation of determination is 0.64. The rainfall-runoff equation was shown as follows:

$$
\begin{aligned}
Q_{Ct.8} = &- 17.4 + 1.29\ R1 + 1.69\ R2 + 1.72\ R3 + 1.31\ R4 + 0.952\ R5 + 0.656\ R6 \\
&+ 0.629\ R7 + 0.256\ R8 + 0.199\ R9 + 0.164\ R10 + 0.023\ R11 + 0.039\ R12 \\
&+ 0.123\ R13 + 0.057\ R14 + 0.043\ R15 + 0.058\ R16 + 0.200\ R17 + 0.192\ R18 \\
&+ 0.184\ R19 + 0.183\ R20 + 0.206\ R21 + 0.230\ R22 + 0.252\ R23 + 0.104\ R24 \\
&+ 0.119\ R25 + 0.167\ R26 + 0.257\ R27 + 0.235\ R28 + 0.286\ R29 + 0.217\ R30
\end{aligned}
$$

where R1, R2, R3....R30 is the daily antecedent rainfall in 1, 2, 3, ... , 30 day,

The discharge and watershed area relationship equation for Sakaekang River Basin was shown as follow:

$$Qs = Q_{Ct.8}*(A_s/A_{ct.8})^{0.7685}$$

Where $Q_{Ct.8}$ is the discharge at the runoff station Ct.8

A_s is the watershed area of Sakaekang River Basin = 4,928 Km^2

A_{Ct8} is the watershed area of the runoff station Ct.8 = 3207 Km^2

In the lateral flow of Upper Chao Phraya River Basin, the oberserved runoff station C.30 was selected from the station which would not disturbed from the backwater effect from Chao Phraya River. The rainfall and runoff data in 1983-1985 was used to formulate the equation. The correlation of determination is 0.53. The rainfall-runoff equation was shown as follows:

$$
\begin{aligned}
Q_{C.30} = &- 2.11 + 0.480\ R1 + 0.253\ R2 + 0.137\ R3 + 0.130\ R4 + 0.0262\ R5 \\
&- 0.0101\ R6 + 0.0303\ R7 + 0.0454\ R8 + 0.137\ R9 + 0.0173\ R10 + 0.0308\ R11 \\
&+ 0.0139\ R12 + 0.0397\ R13 + 0.0147\ R14 - 0.0341\ R15 + 0.0085\ R16 \\
&+ 0.0257\ R17 + 0.0313\ R18 + 0.0162\ R19 + 0.153\ R20 + 0.0423\ R21 \\
&+ 0.0437\ R22 + 0.0860\ R23 + 0.0144\ R24 - 0.0091\ R25 + 0.105\ R26 \\
&+ 0.0547\ R27 + 0.0169\ R28 + 0.0048\ R29 + 0.131\ R30
\end{aligned}
$$

where R1, R2, R3....R30 is the daily antecedent rainfall in 1, 2, 3, ... , 30 day,

The discharge and watershed area relationship equation for Upper Chao Phraya River Basin was shown as follow:

$$Qs = Q_{C.30}*(A_s/A_{c.30})^{0.9366}$$

Where $Q_{Ct.8}$ is the discharge at the runoff station Ct.8

A_s is the watershed area of Sakaekang River Basin = 1,294 Km^2

$A_{C.30}$ is the watershed area of the runoff station C.30 = 219 Km^2

Appendix C

Input variables for the rainfall-runoff model

Table C.1 Initial input parameters for model calibration

Sub basin	Length (KM)	Watershed area (KM(^{2}	Sc (hr)	Tc (hr)	CN	Int (mm)
902	103	2212	128.3	46.31	59.7	23.29
0903/1	36	621	33.3	35.91	42.15	23.77
0903/2	22	235	13.6	29.58	42.15	23.53
0904/1	37	401	23.3	32.92	64.88	24.01
0904/2	40	531	83	34.81	64.88	24.13
0904/3	21	532	83.2	34.82	64.88	38.06
0905/1	26	153	24.6	27.16	62.45	85.64
0905/2	45	442	69.1	33.56	63.39	24.13
906	43	612	95.7	35.81	66.8	55.16
0907/1	34	201	9.1	28.67	64.29	284.76
0907/2	126	3126	141.6	49.62	64.29	57.38
908	49	754	118	37.34	60	86.06
909	136	2229	348.7	46.38	50.43	25.76
0910/1	28	795	79.2	37.73	41.82	28.69
0910/2	22	264	12	30.26	48.44	29.41
0911/1	90	1893	164.4	44.89	76.5	193.66
0911/2	71	757	65.7	37.36	76.5	25
912	112	2458	213.5	47.3	76.14	129.73
913	85	1268	110.1	41.43	73.5	129.11
0914/1	29	415	36	33.13	24.54	325.51
0914/2	73	1699	147.5	43.92	33.46	24.01
0914/3	84	1746	151.6	44.17	33.46	24.5
0914/4	53	690	59.9	36.68	33.46	16.67
915	66	971	72	39.28	9.48	102.01
916	105	1861	150	44.73	59.57	38.82
0917/1	32	415	33.4	33.13	64.47	16.67
0917/2	89	1544	133.9	43.09	64.47	25
0917/3	101	4329	201.9	52.96	64.47	25
0917/4	71	937	72	39	64.47	25

Remark : Sc : Clark storage coefficient, Tc : Clark Time of Concentration, CN : Curve Number, Int : Initial Abstraction

Table C.2 The estimation of parameter function by rainfall pattern

Sub basin	Type	Int		CN		Sc	
		b_0	b	b_0	b	b_0	b
0902	1	0.669	49.07	0.00	35.08	-0.01	62.57
0902	2	-0.29	544.40	0.00	35.15	0.06	7.51
0902	3	-2.58	1172.00	0.00	35.12	-0.04	72.67
0902	4	7.94	-1991.00	7.10	-1971.00	-14.74	4237.00
0902	5	1.39	-70.33	0.00	35.18	1.08	-106.80
0903/1	1	-0.10	546.20	-0.02	43.96	0.04	-11.97
0903/1	2	-0.10	546.20	-0.02	43.96	0.04	-11.970
0903/1	3	0.37	-48.98	0.07	-27.45	0.13	-27.03
0903/1	4	3.16	-559.90	0.41	-101.80	-0.28	130.40
0903/1	5	1.03	118.00	0.24	-48.71	-0.22	95.75
0903/2	1	0.88	79.52	0.01	34.09	0.00	9.14
0903/2	2	0.15	319.60	0.00	35.18	0.00	9.14
0903/2	3	-3.40	1555.00	0.35	-115.90	0.00	9.14
0903/2	4	2.21	-282.20	-0.26	100.80	0.00	9.14
0903/2	5	2.21	-282.20	-0.26	100.80	0.00	9.14
0904/1	1	0.67	-8.52	0.02	21.44	0.00	15.34
0904/1	2	0.31	172.80	0.00	35.18	-0.01	29.53
0904/1	3	-1.53	771.40	0.00	35.18	0.07	-6.05
0904/1	4	1.83	6.98	0.07	18.09	0.04	10.88
0904/1	5	1.83	6.98	0.07	18.09	0.04	10.88
0904/2	1	-0.49	491.50	-0.03	50.32	-0.01	85.34
0904/2	2	1.59	-339.50	0.03	19.96	0.50	-184.10
0904/2	3	-0.65	487.60	0.21	-68.29	-0.26	185.50
0904/2	4	0.60	197.90	0.37	-99.74	0.01	53.22
0904/2	5	1.16	96.41	0.00	36.91	-0.12	94.52
0904/3	1	0.42	119.40	-0.05	52.93	0.21	39.74
0904/3	2	0.64	-13.43	-0.05	71.75	-0.01	96.15
0904/3	3	0.64	-13.43	-0.05	71.75	-0.01	96.15
0904/3	4	2.04	-403.40	0.18	-21.58	0.15	40.12
0904/3	5	0.51	115.30	0.00	35.15	-0.06	92.60
0905/1	1	-1.50	1053.00	0.28	-67.73	0.06	-5.15
0905/1	2	-0.38	743.00	0.01	36.13	-0.01	28.23
0905/1	3	-2.92	1257.00	0.40	-87.32	-0.15	71.36
0905/1	4	-3.78	1367.00	0.12	23.09	-0.04	28.23
0905/1	5	-3.78	1367.00	0.12	23.09	-0.04	28.23

Remark : Int : Initial abstraction, CN : Curve Number, Sc : Clark Storage,

Int = b0*Racc + b , CN = b0*Racc + b, Sc = b0*Racc + b , Racc = accumulative rainfall

Table C.2 The estimation of parameter function by rainfall pattern (continue)

Sub basin	Type	Int		CN		Sc	
		b_0	b	b_0	b	b_0	b
0905/2	1	-1.44	807.60	0.01	35.62	0.10	25.71
0905/2	2	-1.44	807.60	0.01	35.62	0.10	25.71
0905/2	3	-1.64	817.90	0.18	-35.01	-0.39	187.60
0905/2	4	-0.98	541.00	-0.18	69.36	1.08	-184.90
0905/2	5	0.94	147.40	0.03	27.69	-0.13	70.26
0906	1	-1.13	625.80	0.00	35.68	0.00	5.92
0906	2	1.12	-705.70	-0.01	58.34	0.00	5.92
0906	3	-0.79	587.00	0.31	-118.00	0.00	5.92
0906	4	1.89	-311.80	-0.07	77.51	0.00	5.92
0906	5	1.05	60.87	0.04	41.28	0.00	5.92
0907/1	1	-1.29	648.00	0.00	35.18	0.00	9.13
0907/1	2	0.99	149.30	0.00	35.18	0.00	9.13
0907/1	3	3.40	-1523.00	0.00	35.18	0.00	9.13
0907/1	4	3.85	-1534.00	0.00	35.18	0.00	9.13
0907/1	5	2.89	-332.00	0.00	35.18	0.00	9.13
0907/2	1	-1.52	483.00	0.00	35.17	0.09	175.30
0907/2	2	-1.52	483.00	0.00	35.17	0.09	175.30
0907/2	3	3.51	-979.40	-0.01	38.11	2.46	-724.70
0907/2	4	0.63	133.30	0.00	35.17	-2.46	964.10
0907/2	5	-1.04	554.90	0.00	35.18	-0.89	338.00
0908	1	2.16	-133.00	0.00	35.45	0.00	5.32
0908	2	0.48	61.63	0.00	53.88	0.00	5.32
0908	3	0.48	61.63	0.00	53.88	0.00	5.32
0908	4	-1.01	621.50	0.01	49.10	0.00	5.32
0908	5	0.98	102.10	0.11	30.22	0.00	5.32
0909	1	0.63	47.28	0.11	3.84	0.00	4.46
0909	2	0.19	193.90	0.02	8.80	0.00	4.46
0909	3	0.19	193.90	0.02	8.80	0.00	4.46
0909	4	-1.71	696.40	0.54	-131.60	0.00	4.46
0909	5	0.96	304.00	-0.07	60.73	0.00	4.46
0910/1	1	5.54	-1574.00	-0.04	34.76	0.00	37.24
0910/1	2	0.37	129.20	-0.04	49.10	0.15	-99.06
0910/1	3	8.45	-2786.00	0.00	17.71	0.00	37.25
0910/1	4	0.00	500.00	0.00	17.71	0.00	37.29
0910/1	5	2.75	-317.60	-0.52	154.30	-0.39	131.70

Remark : Int : Initial abstraction, CN : Curve Number, Sc : Clark Storage,

Int = b0*Racc + b , CN = b0*Racc + b, Sc = b0*Racc + b , Racc = accumulative rainfall

Table C.2 The estimation of parameter function by rainfall pattern (continue)

Sub basin	**Type**	**Int**		CN		Sc	
		b0	**b**	**b0**	**b**	**b0**	**b**
0910/2	1	1.89	-84.20	0.02	29.12	0.00	12.00
0910/2	2	1.14	111.60	0.03	26.40	0.00	12.00
0910/2	3	0.73	-165.40	0.22	-73.30	0.00	12.00
0910/2	4	0.00	500.00	0.00	35.18	0.00	12.00
0910/2	5	1.06	-65.96	0.02	31.88	0.00	12.00
0911/1	1	-0.29	567.40	0.03	27.43	0.27	243.50
0911/1	2	0.10	240.20	0.00	35.50	1.87	62.47
0911/1	3	0.41	222.40	0.00	35.39	-0.11	1039.00
0911/1	4	0.00	500.00	0.00	35.07	0.00	1000.00
0911/1	5	0.60	222.40	0.00	35.07	0.00	1000.00
0911/2	1	0.00	500.00	0.00	76.50	0.00	65.69
0911/2	2	0.12	409.70	0.00	76.50	0.00	65.69
0911/2	3	3.56	-1058.00	0.00	76.50	0.00	65.69
0911/2	4	0.56	237.00	0.00	76.50	0.00	65.69
0911/2	5	0.56	237.00	0.00	76.50	0.00	65.69
0912	1	-0.56	465.20	0.00	2.82	0.00	13.49
0912	2	0.46	-52.85	0.00	3.01	0.03	10.50
0912	3	1.90	-284.40	0.03	-4.38	-0.03	24.23
0912	4	0.93	45.95	0.00	2.50	0.03	5.62
0912	5	94.89	-17341.00	0.05	-6.17	0.32	-43.75
0913	1	0.00	500.00	0.00	35.01	-0.07	62.42
0913	2	0.97	-262.70	0.01	30.74	0.00	51.25
0913	3	0.97	-262.70	0.01	30.74	0.00	51.25
0913	4	1.52	-448.10	0.00	35.17	0.06	20.21
0913	5	1.52	-448.10	0.00	35.17	0.06	20.21
0914/1	1	0.00	500.00	0.00	35.18	-0.16	113.40
0914/1	2	0.00	500.00	0.00	35.18	-0.16	113.40
0914/1	3	-3.41	1467.00	-1.96	664.30	0.00	7.39
0914/1	4	-2.71	1365.00	-0.07	53.47	0.07	-10.70
0914/1	5	3.00	-423.90	0.00	35.87	0.27	-32.87
0914/2	1	-0.59	487.20	0.02	29.34	0.00	94.97
0914/2	2	0.90	-528.80	0.00	35.18	-0.07	221.20
0914/2	3	-1.54	818.10	0.00	35.18	-0.19	196.60
0914/2	4	2.01	-224.40	0.00	35.18	0.75	-63.14
0914/2	5	-20.85	4345.00	0.00	35.18	-0.29	204.20

Remark : Int : Initial abstraction, CN : Curve Number, Sc : Clark Storage,

Int = b0*Racc + b , CN = b0*Racc + b, Sc = b0*Racc + b , Racc = accumulative rainfall

Table C.2 The estimation of parameter function by rainfall pattern (continued)

Sub basin	Type	Int		CN		Sc	
		b0	b	b0	b	b0	b
0914/3	1	0.00	500.00	0.00	35.02	0.00	450.14
0914/3	2	0.00	500.00	0.00	36.24	0.98	29.07
0914/3	3	0.000	500.00	0.00	36.24	0.98	29.07
0914/3	4	-2.288	990.50	-0.01	37.61	-1.83	956.10
0914/3	5	-20.150	4139.00	0.00	35.17	-40.42	8456.00
0914/4	1	-0.553	285.30	0.03	29.17	0.18	30.16
0914/4	2	0.900	-796.30	-0.07	102.00	0.39	-292.90
0914/4	3	0.050	51.76	-0.03	52.63	0.00	60.53
0914/4	4	1.113	-429.90	-0.15	92.64	0.00	85.92
0914/4	5	0.583	-86.14	-0.32	139.90	-0.26	127.50
0915	1	-0.840	521.50	-0.03	23.24	0.09	24.24
0915	2	0.286	-108.80	-0.03	50.38	-0.03	83.27
0915	3	0.286	-108.80	-0.03	50.38	-0.03	83.27
0915	4	-2.874	1092.00	-0.12	57.71	0.26	-19.05
0915	5	0.00	500.00	-0.21	57.19	2.58	-461.20
0916	1	0.00	22.60	0.00	4.10	0.00	6.55
0916	2	0.00	22.60	0.00	4.95	0.00	6.55
0916	3	0.00	22.60	0.00	5.39	0.00	6.55
0916	4	0.00	22.60	0.00	3.02	0.00	6.55
0916	5	0.00	22.60	0.00	4.28	0.00	6.55
0917/1	1	0.425	157.50	-0.01	38.27	0.00	32.58
0917/1	2	0.00	500.00	0.00	36.03	0.00	33.88
0917/1	3	-0.645	374.30	0.02	28.39	0.00	33.87
0917/1	4	3.978	-909.10	-0.01	41.48	0.00	33.36
0917/1	5	3.978	-909.10	-0.01	41.48	0.00	33.36
0917/2	1	-1.084	818.10	0.00	64.47	0.00	133.92
0917/2	2	1.119	-449.40	0.00	64.47	0.00	133.92
0917/2	3	-4.135	1424.00	0.00	64.47	0.00	133.92
0917/2	4	-1.793	914.50	0.00	64.47	0.00	133.92
0917/2	5	-5.156	1206.00	0.00	64.47	0.00	133.92
0917/3	1	1.551	-249.00	0.00	64.47	0.00	201.92
0917/3	2	0.491	-52.00	0.00	64.47	0.00	201.92
0917/3	3	0.491	-52.00	0.00	64.47	0.00	201.92
0917/3	4	1.381	-68.57	0.00	64.47	0.00	201.92
0917/3	5	-0.973	442.00	0.00	64.47	0.00	201.92

Remark : Int : Initial abstraction, CN : Curve Number, Sc : Clark Storage,

Int = b0*Racc + b , CN = b0*Racc + b, Sc = b0*Racc + b , Racc = accumulative rainfall

Table C.2 The estimation of parameter function by rainfall pattern (continued)

Sub basin	**Type**	**Int**		**CN**		**Sc**	
		b0	**b**	**b0**	**b**	**b0**	**b**
0917/4	1	-1.813	533.70	0.00	64.47	0.00	72.00
0917/4	2	0.339	-12.29	0.00	64.47	0.00	72.00
0917/4	3	0.393	-55.06	0.00	64.47	0.00	72.00
0917/4	4	1.845	-131.90	0.00	64.47	0.00	72.00
0917/4	5	1.845	-131.90	0.00	64.47	0.00	72.00

Remark : Int : Initial abstraction, CN : Curve Number, Sc : Clark Storage,

Int = b0*Racc + b , CN = b0*Racc + b, Sc = b0*Racc + b , Racc = accumulative rainfall

Table C.3 Observed inflow of Sirikit Dam

Year	Inflow (MCM/month)												Annual (MCM)
	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	
1975	64	184	669	1,091	2,767	1,924	887	311	168	167	170	127	8,574
1976	107	186	357	600	1,431	1,596	993	370	223	202	77	133	6,287
1977	118	217	149	530	998	1,047	445	266	144	122	99	95	4,239
1978	129	118	356	1,005	1,804	1,643	735	250	140	123	61	96	6,419
1979	88	237	532	306	1,085	688	311	146	92	96	43	78	3,684
1980	69	130	382	1,069	1,130	2,427	504	223	135	100	34	99	6,312
1981	79	435	380	2,792	1,583	1,171	618	313	155	131	114	55	7,886
1982	137	125	212	695	1,069	1,457	925	255	115	102	69	75	5,212
1983	113	221	196	572	1,251	1,347	896	329	159	130	120	106	5,451
1984	122	221	376	1,230	1,500	1,637	627	271	136	127	105	95	6,454
1985	129	179	220	590	1,868	1,054	439	347	168	124	115	131	5,400
1986	164	466	410	913	866	812	384	208	121	76	66	72	4,457
1987	62	88	161	142	952	661	415	222	90	79	66	50	3,014
1988	89	311	346	818	1,464	636	414	165	104	74	76	63	4,518
1989	47	279	237	643	828	941	492	174	93	84	80	59	3,960
1990	49	240	361	731	884	886	396	220	97	86	45	29	4,042
1991	68	227	261	348	827	846	413	167	86	82	67	64	3,432
1992	45	58	91	418	693	741	440	177	151	94	50	75	3,058
1993	70	126	206	787	643	650	322	131	81	66	58	92	3,228
1994	67	218	411	875	3,272	1,665	632	255	184	119	85	56	7,824
1995	52	134	211	1,019	3,300	2,614	744	510	211	157	149	96	9,297
1996	151	195	388	886	1,593	1,197	745	316	161	124	99	51	5,850
1997	97	107	70	461	1,125	1,368	739	249	134	112	73	72	4,606
1998	96	103	144	504	658	1,155	265	160	84	71	67	74	3,402
1999	116	238	432	459	1,579	2,194	686	285	128	142	146	101	6,500
2000	111	421	517	1,181	1,055	1,433	643	287	176	138	108	202	6,245
2001	83	284	333	1,203	2,741	1,642	610	286	177	146	123	91	7,698
2002	61	547	653	778	1,531	1,668	622	327	220	186	143	159	6,937
2003	102	120	268	934	1,244	1,607	370	216	133	138	105	81	5,343
2004	127	222	666	1,239	1,596	2,225	511	259	178	169	108	112	7,399
2005	114	108	451	686	1,772	1,868	848	322	203	169	125	92	6,809
2006	166	468	287	728	2,357	1,536	936	266	213	164	140	122	7,321
2007	105	265	361	391	1,092	1,035	896	276	184	137	145	104	5,021
2008	136	302	772	1,503	2,095	1,137	654	368	223	181	143	129	7,648
2009	141	205	329	1,104	770	775	466	216	143	136	97	84	4,393
2010	69	115	155	635	2,288	1,761	513	207	189	116	93	117	6,289
2011	133	512	1,094	1,950	3,183	2,341	1,063	375	252	215	144	122	11,285
Mean	99	240	361	866	1,512	1,369	592	258	151	123	97	91	5,757
Max	166	547	1,094	2,792	3,300	2,614	1,063	510	252	215	149	202	11,285
Min	45	58	70	142	643	636	265	131	81	66	34	29	3,014
Stdev	35	131	209	509	759	559	207	80	47	37	34	34	1929

Table C.4 Observed inflow of Bhumibol Dam

Year	Inflow (MCM/month)												Annual (MCM)
	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	
1975	55	123	552	619	1,555	2,493	1,717	857	440	257	162	88	8,914
1976	52	229	164	87	547	1,008	1,555	785	295	358	83	17	5,207
1977	79	181	67	109	528	2,345	1,021	650	282	263	70	52	5,570
1978	3	159	59	1,174	1,497	1,717	1,564	398	262	83	28	17	6,969
1979	12	156	424	149	531	732	952	113	54	22	12	5	3,158
1980	9	350	443	345	625	2,001	1,616	462	310	100	69	17	6,506
1981	170	200	297	679	1,109	955	700	924	384	173	34	27	5,556
1982	72	237	634	307	677	1,503	1,175	425	205	108	46	14	5,332
1983	0	36	68	37	402	1,139	1,485	1,407	370	149	75	9	5,196
1984	18	53	304	189	514	940	1,311	398	191	70	34	13	4,040
1985	24	112	272	414	523	1,241	1,156	1,467	424	193	127	73	6,081
1986	80	297	225	329	679	938	615	286	183	104	30	12	3,746
1987	46	43	224	19	893	1,246	979	793	268	110	40	1	4,625
1988	8	340	769	533	752	848	1,813	714	326	165	67	9	6,337
1989	0	140	368	351	514	664	1,458	448	216	78	23	3	4,275
1990	12	267	292	205	440	1,014	943	465	182	50	9	0	3,867
1991	0	41	247	182	924	1,227	863	505	168	102	25	5	4,289
1992	0	1	31	143	611	1,305	1,208	353	351	151	32	31	4,217
1993	0	49	68	73	174	925	612	164	102	32	12	62	2,357
1994	84	253	510	718	1,997	2,381	988	441	334	168	88	91	8,014
1995	46	234	170	337	1,453	2,191	1,118	468	243	173	244	126	6,874
1996	117	221	444	392	1,003	2,101	1,227	734	247	166	93	105	6,853
1997	119	40	33	296	916	1,003	1,164	334	146	80	51	27	4,091
1998	2	13	4	99	262	690	137	69	36	4	0	2	1,321
1999	5	486	370	148	871	1,168	1,232	1,271	251	110	95	46	6,224
2000	177	696	645	484	623	1,096	950	518	194	99	29	134	5,469
2001	0	234	150	409	1,406	759	746	530	194	126	48	12	4,630
2002	16	379	251	326	945	2,990	1,112	1,287	589	384	205	149	8,685
2003	66	134	126	354	444	1,135	424	137	8	3	0	0	2,765
2004	0	350	663	468	796	1,455	598	199	109	26	18	24	4,775
2005	71	51	238	466	953	2,659	1,231	848	308	143	59	40	7,147
2006	150	643	515	705	1,274	2,763	1,634	440	254	164	102	19	8,514
2007	1	994	447	321	651	1,347	1,834	482	221	75	36	0	6,418
2008	10	560	289	249	709	1,112	1,589	1,064	218	44	0	24	5,886
2009	29	390	688	580	664	1,452	1,970	376	89	30	0	0	6,239
2010	0	0	21	150	1,124	1,509	2,067	427	121	12	4	157	5,640
2011	236	1,010	908	979	2,592	2,843	2,895	687	407	283	82	5	12,691
2012	59	331	305	326	660	1,516	784	338	126	28	38	56	4,510
Max	236	1,010	908	1,174	2,592	2,990	2,895	1,467	589	384	244	157	12,691
Min	0	0	4	19	174	664	137	69	8	3	0	0	1,321
Mean	48	264	323	362	864	1,484	1,222	586	240	123	57	39	5,605

Table C.5 Monthly mean observed runoff of N.12A station

Year	Monthly mean runoff (MCM/month)												Annual (MCM)
	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	
1979	904	822	515	577	743	465	499	533	306	206	168	274	5,387
1980	278	319	244	229	206	792	492	324	347	474	584	734	5,545
1981	801	739	785	701	1,347	597	464	540	344	450	614	829	8,353
1982	944	636	299	504	688	321	292	345	282	475	587	696	6,215
1983	1,090	689	286	521	376	207	126	73	49	165	471	816	4,571
1984	793	500	293	357	682	888	311	522	151	441	712	1,093	6,992
1985	1,041	605	287	287	214	340	93	126	115	191	593	917	4,550
1986	781	759	727	608	405	362	442	735	237	332	776	762	6,894
1987	750	676	321	481	475	206	100	178	36	170	560	445	3,882
1988	234	190	99	209	169	218	207	139	60	182	355	424	2,863
1989	611	631	148	203	482	519	203	290	86	219	402	793	4,747
1990	770	663	516	443	490	617	354	339	176	210	530	729	5,694
1991	627	339	148	328	382	112	175	249	135	194	338	476	3,306
1992	432	286	60	76	83	181	58	276	267	187	440	544	2,918
1993	459	408	299	397	810	369	108	458	134	151	229	265	3,771
1994	143	150	157	85	393	538	235	490	345	378	656	901	5,086
1995	758	649	482	319	1,234	2,440	825	495	365	466	745	953	9,926
1996	955	771	798	610	824	668	286	334	207	331	575	770	6,927
1997	752	658	384	421	441	364	290	427	308	391	643	623	5,524
1998	574	293	202	173	349	228	178	306	203	344	415	523	3,454
1999	238	127	63	112	249	450	84	69	78	540	894	996	4,401
2000	738	490	366	283	361	249	335	322	490	782	958	824	6,521
2001	1,061	430	158	405	1,034	1,462	260	196	473	693	903	1,121	8,197
2002	1,063	840	419	665	578	364	273	297	241	723	836	910	6,768
2003	622	891	475	545	456	335	203	559	483	482	639	755	6,568
2004	743	417	219	444	243	505	301	598	748	828	795	884	6,622
2005	639	707	394	356	238	343	248	253	570	723	744	854	6,174
2006	744	346	229	156	321	418	545	215	662	831	646	678	5,614
2007	567	211	455	482	539	347	260	390	496	659	652	632	5,895
2008	772	471	445	474	329	276	215	241	706	878	868	1,014	6,941
2009	1,024	838	523	416	563	510	420	446	713	692	716	689	6,872
2010	346	233	306	275	341	286	197	162	436	863	919	775	5,481
2011	378	168	198	562	2,348	2,416	1,258	556	959	1,504	1,630	1,043	12,640
2012	760	774	729	545	466	284	213	528	775	490	654	750	6,208
Max	1,090	891	798	701	2,348	2,440	1,258	735	959	1,504	1,630	1,121	12,640
Min	143	127	60	76	83	112	58	69	36	151	168	265	2,863
Mean	688	521	354	390	555	549	310	353	353	490	654	750	5,927

Table C.6 Monthly mean observed runoff of N.27A station

Year	Monthly mean runoff (MCM/month)												Annual (MCM)
	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	
1979	572	614	500	480	747	734	639	378	267	179	184	251	5,167
1980	193	245	248	335	621	1,550	517	208	215	274	365	462	5,751
1981	711	902	858	923	1,654	736	526	637	381	413	572	743	9,209
1982	864	628	301	453	618	592	377	372	312	448	538	552	6,235
1983	1,044	731	313	405	346	343	315	165	85	139	377	728	4,594
1984	648	448	408	300	485	912	477	516	190	395	574	891	6,581
1985	987	648	361	390	205	444	337	288	248	187	449	774	4,905
1986	574	660	769	586	335	341	175	495	257	239	573	485	5,468
1987	554	524	356	343	456	294	118	183	123	194	445	349	3,506
1988	121	345	153	239	119	62	63	39	78	124	130	104	1,761
1989	305	591	278	211	170	352	26	142	84	147	248	598	3,287
1990	440	495	681	350	198	555	164	206	178	127	335	475	4,219
1991	455	312	183	244	435	184	66	152	177	158	206	242	2,597
1992	238	179	103	94	193	185	93	69	206	96	213	310	2,116
1993	377	399	317	296	554	440	21	316	206	129	187	245	3,236
1994	126	212	494	172	608	1,140	161	333	375	254	469	661	5,439
1995	559	508	478	261	1,444	3,011	1,247	586	418	314	504	741	10,267
1996	756	778	916	548	951	1,423	761	461	301	178	336	516	7,703
1997	535	553	327	298	362	529	349	341	331	188	430	408	4,588
1998	472	305	207	266	253	159	51	228	238	282	352	418	3,028
1999	268	327	137	105	300	896	194	111	16	377	670	766	4,523
2000	623	622	532	344	424	672	432	276	392	540	615	648	6,201
2001	704	488	272	403	1,265	1,699	506	248	444	515	564	739	7,822
2002	677	608	403	470	757	1,118	419	401	188	392	511	606	6,271
2003	398	657	519	549	594	663	169	422	314	326	443	506	5,691
2004	530	354	446	491	259	968	248	499	653	580	581	664	6,278
2005	535	623	397	360	244	770	362	232	387	500	521	600	5,637
2006	642	672	505	330	496	1,520	1,490	283	503	592	507	508	7,891
2007	485	467	434	425	505	600	560	258	396	421	395	383	5,373
2008	530	314	294	300	295	451	274	343	424	515	482	603	4,909
2009	615	508	364	217	177	341	295	204	314	269	261	208	3,330
2010	172	224	290	240	492	460	273	131	289	607	614	544	4,674
2011	278	199	162	431	2,642	2,858	1,754	387	530	808	1,037	673	11,480
2012	358	543	553	387	353	537	222	327	416	330	445	527	4,640
Max	1,044	902	916	923	2,642	3,011	1,754	637	653	808	1,037	891	11,480
Min	121	179	103	94	119	62	21	39	16	96	130	104	1,761
Mean	510	491	399	360	575	810	402	301	292	330	445	527	5,423

Table C.7 Monthly mean observed runoff of N.5A station

Year	Monthly mean runoff (MCM/month)												Annual (MCM)
	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	
1979	817	796	737	664	985	881	680	612	409	259	192	282	6,786
1980	288	388	501	660	1,269	2,572	1,068	370	451	376	472	598	9,399
1981	674	938	959	1,278	2,198	1,074	736	725	518	451	564	749	11,079
1982	890	681	394	508	748	1,096	719	498	460	491	565	610	7,790
1983	1,020	762	387	507	554	828	701	352	259	208	421	744	6,462
1984	739	508	663	463	760	1,373	993	657	392	471	618	946	8,852
1985	1,009	663	405	630	625	856	885	635	473	265	435	783	7,333
1986	679	906	1,090	836	701	794	340	645	456	318	671	609	7,923
1987	557	568	387	322	655	586	351	243	244	188	447	354	4,496
1988	152	596	303	401	356	227	310	113	254	188	169	130	3,407
1989	361	646	573	328	312	575	216	252	258	231	309	591	4,809
1990	517	700	1,181	637	457	1,049	452	332	336	192	404	568	6,857
1991	550	406	283	309	867	675	382	230	287	200	237	275	4,419
1992	268	206	156	144	560	458	277	115	306	123	248	361	3,342
1993	387	444	434	375	624	813	140	349	270	139	198	271	4,184
1994	128	334	946	479	1,195	1,955	463	409	482	278	496	687	8,389
1995	667	650	688	458	2,226	3,885	2,118	902	511	350	573	857	14,080
1996	861	1,001	1,188	770	1,531	2,236	1,474	706	466	265	425	614	11,264
1997	588	594	389	436	667	968	741	428	430	192	433	424	6,206
1998	503	364	239	558	453	396	137	279	232	242	336	416	3,985
1999	335	521	356	218	632	1,569	668	394	103	412	716	821	7,124
2000	714	884	811	684	750	1,330	873	431	472	593	666	737	8,974
2001	742	600	440	678	1,810	2,130	863	376	509	562	602	778	10,069
2002	719	681	523	644	1,225	2,022	880	598	264	446	578	676	8,983
2003	445	707	651	744	915	1,128	374	484	364	367	485	525	7,285
2004	541	448	747	704	575	1,400	518	564	706	611	603	681	8,158
2005	600	673	583	554	494	1,292	766	381	442	549	542	619	7,420
2006	527	621	565	499	708	1,935	1,950	437	452	498	428	434	9,071
2007	544	678	564	580	777	1,078	1,069	365	460	463	439	403	7,420
2008	543	400	390	442	580	806	533	427	446	524	661	638	6,462
2009	615	525	515	419	311	455	443	254	406	394	343	349	4,743
2010	329	305	334	293	629	781	585	390	438	719	771	711	6,518
2011	446	362	397	702	3,105	3,828	2,501	624	687	996	1,167	731	15,102
2012	412	624	683	528	420	705	300	392	525	381	491	575	5,624
Max	1,020	1,001	1,188	1,278	3,105	3,885	2,501	902	706	996	1,167	946	15,102
Min	128	206	156	144	311	227	137	113	103	123	169	130	3,342
Mean	564	594	572	543	902	1,287	750	440	405	381	491	575	7,471

Table C.8 Monthly mean observed runoff of N.7A station

Year	Monthly mean runoff (MCM/month)												Annual (MCM)
	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	
1979	872	860	984	765	1,165	1,150	813	687	474	265	174	255	7,884
1980	292	422	658	976	1,645	3,137	1,862	593	565	404	483	630	12,118
1981	744	1,016	1,084	1,463	2,835	1,465	922	863	701	526	602	816	13,198
1982	905	712	473	564	844	1,515	1,341	791	571	540	597	618	9,551
1983	984	797	471	599	805	1,223	1,171	827	460	302	468	757	8,593
1984	713	551	848	616	859	1,590	1,417	903	520	496	611	907	10,298
1985	982	724	524	806	925	1,187	1,397	1,550	832	321	464	763	10,159
1986	666	975	1,174	938	834	969	408	667	521	281	629	592	8,534
1987	546	567	429	333	719	939	985	397	365	213	419	364	5,890
1988	161	708	365	499	570	426	641	318	334	199	183	157	4,734
1989	334	676	881	430	353	693	396	332	324	224	275	562	5,686
1990	539	751	1,503	880	633	1,302	712	426	416	183	399	592	8,302
1991	504	399	321	303	933	1,115	616	332	337	204	228	268	5,306
1992	252	12	99	137	714	764	583	279	358	133	222	349	4,051
1993	401	481	530	421	696	1,139	300	408	348	140	209	279	5,102
1994	152	432	1,435	913	1,573	2,838	1,245	568	702	549	628	737	12,339
1995	719	739	774	675	2,600	4,142	3,154	1,284	845	762	686	892	17,569
1996	1,016	1,357	1,621	1,045	1,900	2,866	3,167	1,359	724	301	481	704	16,259
1997	734	698	421	566	895	1,562	1,435	645	562	235	499	519	8,525
1998	491	378	231	800	667	764	325	355	300	283	303	383	5,248
1999	459	689	595	325	951	2,155	1,452	1,122	245	439	799	914	10,540
2000	853	1,254	1,188	1,216	1,056	2,382	1,962	1,079	650	743	815	916	14,166
2001	906	806	705	963	2,826	3,413	2,109	971	660	666	730	942	15,682
2002	890	843	778	879	1,777	4,019	2,418	1,317	502	512	725	840	15,152
2003	544	830	924	1,042	1,358	1,949	1,033	640	423	404	568	611	10,424
2004	643	593	1,371	1,103	1,321	1,897	1,251	722	861	748	721	820	12,139
2005	731	816	753	800	870	2,029	1,708	607	555	693	662	757	10,999
2006	748	920	1,197	1,243	1,302	3,076	3,305	1,086	716	746	653	664	15,594
2007	686	995	850	1,037	1,310	2,284	2,553	754	780	597	567	509	12,930
2008	694	576	560	800	632	1,822	1,682	1,284	643	722	849	839	11,161
2009	752	713	810	856	547	986	1,764	609	507	511	411	416	8,510
2010	380	339	360	345	1,345	2,195	1,736	1,152	576	907	1,007	973	11,565
2011	561	737	1,020	1,539	3,539	3,863	3,390	1,194	836	1,169	1,364	906	19,558
2012	549	724	1,004	826	779	1,715	1,020	523	667	467	558	644	8,928
Max	1,016	1,357	1,621	1,539	3,539	4,142	3,390	1,550	861	1,169	1,364	973	19,558
Min	152	12	99	137	353	426	300	279	245	133	174	157	4,051
Mean	630	709	792	785	1,229	1,899	1,479	784	555	467	558	644	10,491

Table C.9 Monthly mean observed runoff of N.60 station

Year	Monthly mean runoff (MCM/month)												Annual (MCM)
	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	
1979	957	907	648	666	953	757	683	593	399	267	283	404	6,993
1980	433	481	371	349	346	1,106	674	418	442	538	659	821	7,076
1981	871	836	924	779	1,637	898	640	599	438	514	686	907	9,849
1982	991	749	427	599	892	604	431	436	374	540	662	787	7,613
1983	1,113	794	414	615	539	483	229	208	132	225	560	896	5,957
1984	864	635	421	466	885	1,208	454	584	238	505	777	1,146	8,391
1985	1,072	723	415	402	355	624	189	252	201	252	668	987	5,922
1986	854	854	833	733	569	558	488	787	260	319	780	747	7,646
1987	719	657	335	498	571	403	183	213	61	167	568	453	4,358
1988	249	376	176	361	317	286	278	171	89	181	339	356	3,518
1989	590	696	207	231	468	681	273	362	119	230	441	813	5,244
1990	723	673	634	488	503	858	425	376	200	186	557	763	6,334
1991	672	405	205	344	493	253	239	287	176	206	345	492	3,933
1992	488	343	149	126	206	298	164	194	255	136	322	466	3,098
1993	440	424	351	445	841	574	172	492	207	158	242	281	4,342
1994	155	214	368	168	630	873	301	539	450	423	710	1,000	6,587
1995	911	752	649	392	1,547	2,892	1,110	685	509	536	874	1,205	12,355
1996	1,204	1,087	1,143	818	1,300	1,444	614	556	330	424	726	953	10,185
1997	789	717	443	521	505	547	421	501	361	385	660	670	6,363
1998	632	359	231	216	396	283	182	331	226	328	410	499	3,803
1999	342	314	100	152	385	808	208	129	97	626	1,045	1,158	5,926
2000	903	727	537	396	537	510	460	397	575	826	951	915	7,944
2001	1,115	595	245	488	1,391	1,954	480	285	558	778	958	1,166	10,098
2002	1,200	1,011	501	768	800	647	319	371	232	782	951	1,035	8,181
2003	765	1,098	684	818	812	744	335	757	655	648	806	921	9,054
2004	777	514	380	559	311	866	384	696	865	895	866	987	8,096
2005	772	851	543	526	327	638	349	325	674	826	835	967	7,811
2006	952	771	484	378	608	1,062	1,113	392	864	995	873	892	9,276
2007	844	521	671	665	708	597	497	538	781	919	837	867	8,543
2008	943	595	526	572	434	449	369	469	848	1,023	939	1,138	8,463
2009	1,103	924	580	410	495	565	436	404	718	699	676	606	6,944
2010	431	317	406	402	719	540	400	294	652	1,199	1,194	1,076	7,974
2011	547	344	340	766	3,152	3,237	1,715	713	1,194	1,567	1,727	1,208	15,964
2012	975	1,123	1,055	726	544	565	202	709	1,019	555	725	836	8,059
Max	1,204	1,123	1,143	818	3,152	3,237	1,715	787	1,194	1,567	1,727	1,208	15,964
Min	155	214	100	126	206	253	164	129	61	136	242	281	3,098
Mean	776	658	482	495	740	847	453	443	447	555	725	836	7,409

Table C.10 Monthly mean observed runoff of N.67 station

Year	Monthly mean runoff (MCM/month)												Annual (MCM)
	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	
1979	832	1,003	1,357	1,098	1,508	1,461	1,342	824	504	254	133	229	10,008
1980	293	658	1,016	1,431	2,774	4,485	3,245	1,411	636	426	442	658	17,983
1981	800	1,070	1,590	1,971	3,844	1,998	2,811	2,180	1,572	528	617	521	19,535
1982	833	817	609	637	1,238	2,451	3,250	914	1,313	648	607	631	14,004
1983	889	968	510	1,156	1,290	1,911	2,383	2,805	1,434	328	483	540	14,484
1984	677	816	1,752	1,108	1,187	2,159	2,313	1,841	1,152	485	668	886	15,288
1985	922	753	1,065	1,302	1,233	1,854	2,549	3,603	1,127	333	412	484	15,427
1986	713	1,344	1,728	1,439	1,403	2,944	4,378	1,161	670	242	637	619	17,121
1987	558	612	1,310	371	910	3,552	4,795	1,705	692	259	490	344	15,258
1988	216	917	1,385	324	1,044	943	1,839	453	637	398	146	140	8,565
1989	339	770	1,375	929	715	999	1,238	1,286	414	378	346	401	9,167
1990	317	931	1,998	820	1,021	1,783	1,597	1,181	634	182	322	610	11,591
1991	512	444	189	436	1,418	1,782	1,630	808	544	224	205	257	8,190
1992	253	19	90	166	1,146	757	1,569	1,022	654	215	177	323	6,527
1993	390	510	537	577	868	1,636	1,124	625	376	131	213	249	7,043
1994	197	598	2,367	1,662	2,586	4,991	2,627	1,013	869	512	540	716	19,224
1995	743	802	698	743	3,326	4,928	4,650	2,249	1,118	738	689	898	21,795
1996	956	1,468	1,811	1,245	2,192	3,712	5,313	2,588	1,039	254	520	801	21,696
1997	754	669	391	889	1,058	1,817	2,042	997	789	239	442	534	10,394
1998	527	410	248	1,004	861	1,201	1,283	686	436	220	287	343	7,396
1999	418	1,012	1,199	664	1,386	2,721	2,804	2,642	1,212	531	792	927	16,646
2000	755	1,391	1,624	1,685	1,402	3,008	2,980	2,065	798	650	720	961	18,032
2001	747	1,022	1,120	1,130	2,685	3,267	3,117	2,030	942	587	630	830	18,173
2002	813	798	997	914	1,634	3,213	2,953	1,958	992	562	655	763	16,003
2003	566	748	916	1,128	1,474	2,205	1,961	872	437	340	519	519	11,676
2004	557	671	1,803	1,695	2,207	2,394	2,319	900	691	380	380	430	14,178
2005	306	324	396	503	1,106	2,329	2,528	1,393	524	520	500	559	11,375
2006	693	1,027	1,642	1,810	1,691	3,359	3,906	2,010	833	779	710	728	19,197
2007	702	1,605	1,137	1,439	1,472	2,673	3,337	1,533	611	564	566	510	16,108
2008	659	801	868	1,030	1,494	2,283	2,739	2,505	801	668	732	807	15,386
2009	658	689	921	1,152	825	1,305	2,567	1,162	499	479	386	386	10,662
2010	291	261	270	280	1,717	2,805	2,616	1,799	672	708	717	854	13,290
2011	608	1,124	1,651	2,037	3,516	3,898	4,084	2,603	1,020	1,265	1,444	1,094	23,735
2012	643	687	1,187	1,016	1,027	2,266	1,703	625	566	455	519	592	10,645
Max	956	1,605	2,367	2,037	3,844	4,991	5,313	3,603	1,572	1,265	1,444	1,094	23,735
Min	197	19	90	166	715	757	1,124	453	376	131	133	140	6,527
Mean	592	816	1,111	1,053	1,625	2,503	2,694	1,572	800	455	519	592	14,288

Table C.11 Monthly mean observed runoff of N.1 station

Year	Monthly mean runoff (MCM/month)												Annual (MCM)
	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	
1990	25	62	159	537	524	423	199	127	66	40	22	21	2,203
1991	23	101	138	283	578	533	220	97	63	37	23	19	2,106
1992	15	16	33	307	402	404	224	117	114	64	36	46	1,801
1993	39	62	109	657	423	305	194	88	46	37	25	33	2,018
1994	39	96	279	765	1,998	886	398	162	120	53	64	59	4,913
1995	34	43	129	819	2,135	1,215	443	256	115	66	41	28	5,335
1996	45	59	160	611	1,019	550	411	153	82	56	31	27	3,197
1997	36	57	30	299	695	710	337	121	60	43	24	17	2,429
1998	35	37	75	320	385	601	141	73	46	29	18	16	1,768
1999	26	109	320	327	1,093	1,238	397	152	73	48	33	26	3,845
2000	29	167	253	823	546	766	284	128	74	48	21	37	3,173
2001	28	95	144	680	1,421	905	355	161	84	59	34	23	3,988
2002	24	312	464	673	1,030	927	282	172	126	79	38	53	4,193
2003	37	33	103	462	695	796	193	81	44	34	20	13	2,503
2004	29	75	250	686	922	1,375	273	110	68	47	24	19	3,866
2005	17	29	148	367	1,022	871	398	145	76	66	38	23	3,231
2006	48	95	85	465	1,780	748	437	148	84	53	29	22	3,970
2007	22	97	171	228	637	687	574	135	48	21	37	8	2,674
Max	48	312	464	823	2,135	1,375	574	256	126	79	64	59	5,335
Min	15	16	30	228	385	305	141	73	44	21	18	8	1,768
Mean	31	86	170	517	961	775	320	135	77	49	31	27	3,178

Table C.12 Monthly mean observed runoff of N.13A station

Year	Monthly mean runoff (MCM/month)												Annual (MCM)
	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	
1990	46	144	306	894	760	739	320	216	125	86	54	41	3,730
1991	44	179	266	401	935	869	390	182	105	77	50	34	3,517
1992	28	33	58	578	698	734	355	157	139	84	53	60	2,994
1993	46	96	242	1,003	805	605	317	167	98	65	40	59	3,548
1994	50	155	376	1,228	3,999	2,187	812	323	234	98	64	56	9,590
1995	58	96	227	1,389	4,466	2,861	960	630	312	173	88	69	11,376
1996	105	125	381	1,490	2,360	1,343	846	365	171	117	74	66	7,424
1997	85	116	86	714	1,779	1,914	961	292	158	109	76	60	6,350
1998	85	93	137	796	967	1,525	340	144	107	86	58	51	4,365
1999	63	189	651	625	2,491	3,151	974	377	177	102	75	66	8,928
2000	50	377	661	1,890	1,558	2,158	873	375	180	116	70	111	8,434
2001	65	208	357	1,813	4,072	2,761	962	441	233	160	92	69	11,229
2002	61	785	1,187	1,572	2,834	2,868	886	481	320	205	114	126	11,458
2003	80	93	304	1,331	1,894	2,329	480	211	127	93	63	46	7,046
2004	74	173	737	1,673	2,238	2,710	554	225	134	94	63	54	8,714
2005	59	88	433	910	2,390	2,345	1,018	374	191	130	90	62	8,154
2006	123	373	221	1,020	3,351	1,681	899	297	166	117	76	58	8,324
2007	66	245	426	495	1,491	1,359	1,168	335	178	115	116	50	6,044
Max	123	785	1,187	1,890	4,466	3,151	1,168	630	320	205	116	126	11,458
Min	28	33	58	401	698	605	317	144	98	65	40	34	2,994
Mean	66	198	392	1,101	2,172	1,897	729	311	175	113	73	63	7,290

Table C.13 Monthly mean observed runoff of W.4A station

Year	Monthly mean runoff (MCM/month)												Annual (MCM)
	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	
1979	3.0	16.0	67.6	11.5	22.5	41.5	36.7	7.7	3.7	2.3	2.3	4.8	218
1980	1.5	6.0	23.5	20.4	28.9	174.9	85.5	24.8	9.7	3.8	2.7	2.1	384
1981	1.8	26.4	14.3	95.2	149.2	77.3	57.1	42.9	19.5	7.4	5.4	3.9	504
1982	5.6	8.9	8.5	3.8	4.9	42.6	64.1	12.9	4.1	3.4	2.9	1.9	159
1983	0.9	0.7	5.9	0.8	14.2	102.2	82.6	55.1	13.8	4.6	3.1	1.9	287
1984	1.8	5.5	8.5	4.1	15.0	52.9	82.5	20.7	7.4	3.4	2.4	1.5	206
1985	2.2	4.8	16.0	9.9	8.2	38.0	85.7	103.7	31.6	10.2	6.6	4.9	323
1986	3.9	12.5	6.1	6.8	37.3	101.4	37.8	13.5	4.8	2.7	2.4	1.9	229
1987	1.6	2.4	9.5	4.6	51.8	143.8	80.6	55.7	15.7	5.2	2.9	1.5	376
1988	1.8	15.6	92.3	82.7	56.9	68.2	137.6	37.5	14.3	5.4	3.8	2.7	519
1989	2.0	5.3	53.9	12.4	46.4	54.8	137.7	29.5	9.6	3.1	1.8	2.2	358
1990	1.5	7.7	6.5	3.0	7.0	86.5	57.3	39.2	7.3	2.7	0.9	0.0	220
1991	2.1	1.0	1.4	0.5	12.1	72.2	51.2	18.6	5.9	4.0	3.4	3.2	175
1992	1.6	0.5	0.0	0.0	8.7	51.0	92.6	20.8	16.8	10.7	3.6	3.0	210
1993	2.5	1.8	1.8	3.1	3.3	46.9	63.1	12.7	4.8	2.4	8.7	4.3	157
1994	4.2	46.4	89.9	73.3	158.9	201.4	77.5	20.7	14.4	9.1	6.0	4.5	704
1995	2.1	4.7	1.1	5.0	99.7	189.7	64.2	37.4	13.4	6.3	4.3	3.3	437
1996	7.5	8.1	18.2	15.7	56.8	189.3	135.4	54.4	14.6	7.0	5.4	4.1	512
1997	2.9	2.0	1.6	1.8	7.6	27.0	86.1	10.8	6.8	3.1	2.0	0.9	156
1998	6.0	9.4	2.4	20.3	29.5	183.1	37.6	21.0	8.9	2.8	1.1	1.2	320
1999	3.2	43.5	13.0	3.7	6.5	300.8	336.9	333.2	30.3	3.5	3.0	2.9	1,097
2000	20.1	149.6	237.8	75.8	144.8	307.3	271.8	137.0	27.3	13.6	10.3	23.2	1,414
2001	15.5	150.5	26.8	49.5	380.2	271.8	295.1	303.3	53.0	34.1	21.3	15.4	1,607
2002	6.2	37.1	70.3	31.6	104.4	874.8	290.3	316.4	151.6	64.6	32.1	27.9	2,022
2003	21.3	31.9	34.2	46.6	78.3	341.1	97.2	28.8	6.8	8.4	5.6	4.3	686
2004	2.5	17.8	63.5	61.1	168.6	282.4	129.4	38.2	23.3	11.3	14.1	20.1	843
2005	13.5	11.1	19.7	36.4	96.6	636.8	424.9	158.0	49.3	25.7	18.3	32.0	1,531
2006	21.9	234.5	206.5	135.4	331.3	1,172.2	646.1	72.6	27.3	13.4	7.3	5.0	2,868
2007	16.6	178.4	59.4	75.8	79.5	226.5	203.5	60.5	16.9	8.6	7.9	4.4	923
2008	1.8	9.1	7.6	2.8	12.4	133.9	234.3	240.3	9.1	8.0	4.8	5.7	685
2009	17.4	37.7	82.8	68.5	54.8	176.6	361.1	46.3	8.5	9.8	1.5	1.8	851
2010	2.1	0.4	3.0	8.5	361.2	426.4	362.9	89.3	27.2	6.9	3.6	10.6	1,308
2011	42.4	482.3	178.9	257.8	1,091.9	1,005.0	848.9	158.3	56.0	24.6	38.8	26.5	4,169
2012	17.6	115.6	164.1	60.6	72.1	572.0	231.3	82.2	33.8	10.1	7.3	7.1	1,356
Max	42.4	482.3	237.8	257.8	1,091.9	1,172.2	848.9	333.2	151.6	64.6	38.8	32.0	4,169
Min	0.9	0.4	0.0	0.0	3.3	27.0	36.7	7.7	3.7	2.3	0.9	0.0	156
Mean	7.6	49.6	47.0	37.9	111.8	255.1	184.9	79.5	22.0	10.1	7.3	7.1	818

Table C.14 Monthly mean observed runoff of P.17 station

Year	Monthly mean runoff (MCM/month)												Annual (MCM)
	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	
1979	884	874	981	825	722	891	881	835	665	349	281	336	7,921
1980	283	771	915	587	662	1,194	1,512	488	333	298	486	745	8,638
1981	648	873	817	509	843	632	664	1,505	483	405	615	875	8,965
1982	744	704	634	823	866	687	703	781	360	400	705	1,029	8,428
1983	734	668	496	408	432	991	2,147	1,810	479	190	604	851	9,876
1984	800	641	422	401	503	555	764	363	219	271	495	746	5,951
1985	570	491	366	387	387	712	1,211	741	317	230	588	798	6,967
1986	740	1,239	796	673	673	826	859	750	479	261	547	881	8,832
1987	850	538	501	581	764	1,023	667	598	267	243	305	1,007	7,143
1988	648	563	617	516	404	1,076	1,881	416	209	417	644	1,110	8,997
1989	1,142	695	449	303	746	623	1,165	616	277	491	484	761	7,447
1990	838	664	654	328	347	670	983	645	308	491	602	761	6,969
1991	517	273	168	168	341	465	717	403	409	372	475	657	4,979
1992	533	424	129	76	444	225	1,291	465	362	227	376	562	5,205
1993	622	529	538	294	390	347	490	506	185	112	154	215	3,884
1994	126	455	819	473	660	1,670	835	394	453	233	361	691	7,718
1995	673	637	630	546	669	1,733	1,144	563	465	447	762	1,061	9,609
1996	951	888	902	622	767	2,236	2,010	1,080	552	493	763	871	11,847
1997	664	736	617	516	643	1,106	1,351	781	479	491	602	761	8,131
1998	48	466	218	207	350	367	343	297	192	195	272	227	3,293
1999	159	549	374	128	206	518	1,679	1,684	136	169	435	540	6,959
2000	542	653	610	276	769	970	1,405	663	364	524	707	776	8,437
2001	720	1,227	816	422	901	633	1,153	1,507	461	494	635	909	9,877
2002	718	704	385	405	371	2,406	1,266	2,082	1,131	710	808	1,002	12,130
2003	860	1,160	1,062	732	643	1,166	807	708	730	649	663	678	9,599
2004	600	589	445	575	659	804	407	457	310	448	405	429	6,032
2005	505	453	743	485	474	1,296	1,212	769	538	680	574	523	8,262
2006	515	1,084	1,106	749	786	2,458	3,530	531	1,300	1,378	1,023	982	15,568
2007	641	1,276	957	1,237	786	1,368	1,885	401	739	887	834	848	12,223
2008	1,005	1,144	703	683	529	933	1,425	1,598	587	783	709	740	10,590
2009	757	704	548	543	517	1,016	1,688	377	748	826	823	814	9,035
2010	431	367	276	275	905	1,210	1,979	345	449	511	493	414	7,856
2011	333	1,009	748	842	2,081	3,323	4,331	981	782	1,565	1,723	1,453	18,838
2012	779	1,048	501	312	326	1,391	739	517	626	492	605	759	7,316
Max	1,142	1,276	1,106	1,237	2,081	3,323	4,331	2,082	1,300	1,565	1,723	1,453	18,838
Min	48	273	129	76	206	225	343	297	136	112	154	215	3,293
Mean	635	738	616	497	634	1,104	1,327	784	482	492	605	759	8,633

Table C.15 Monthly mean observed runoff of Y.17 station

Year	Monthly mean runoff (MCM/month)												Annual (MCM)
	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	
1979	0.4	42.5	200.6	150.8	220.3	264.9	214.2	33.7	12.9	12.8	0.0	0.0	1,157
1980	3.7	16.3	274.5	437.4	847.6	1,298.4	1,326.0	569.3	102.2	26.6	9.4	8.5	4,959
1981	42.7	74.0	76.7	395.8	852.9	505.6	1,647.7	1,073.0	464.8	31.2	8.4	0.7	5,155
1982	23.9	46.3	208.3	32.2	315.9	346.1	1,647.8	77.8	558.7	153.1	0.1	0.3	3,393
1983	6.2	7.0	103.6	459.9	251.7	639.8	983.0	1,095.4	912.1	19.1	37.5	2.8	4,557
1984	45.4	58.6	822.8	416.3	314.1	452.0	611.9	764.8	617.6	25.7	13.1	0.6	4,121
1985	23.7	17.7	451.5	450.2	315.0	629.5	906.8	1,255.3	62.0	0.5	44.4	0.3	4,155
1986	22.3	74.9	440.3	221.4	413.5	2,031.4	3,967.3	89.6	110.0	31.3	14.1	2.7	7,398
1987	1.7	19.2	833.7	21.6	173.5	2,447.3	3,596.1	1,014.3	86.1	1.8	23.7	24.5	8,272
1988	30.5	51.2	908.0	34.3	204.6	486.0	963.6	92.5	291.9	176.7	6.1	10.3	3,236
1989	10.8	75.9	446.3	422.3	233.7	274.4	628.3	693.1	65.0	123.4	16.8	25.7	3,029
1990	23.7	90.2	423.0	143.4	298.3	438.0	608.7	383.8	95.8	17.8	4.5	2.4	2,521
1991	15.4	57.1	96.7	30.0	171.6	616.2	784.6	349.6	72.6	32.9	9.2	23.5	2,250
1992	5.9	8.3	8.2	0.2	411.0	315.7	707.0	570.3	93.6	72.7	3.3	0.0	2,190
1993	0.0	16.3	58.8	59.2	53.0	345.2	421.7	99.3	33.0	1.6	0.0	0.2	1,103
1994	14.7	92.2	698.6	667.1	686.7	2,017.0	1,019.1	315.9	97.9	17.7	2.6	10.3	5,634
1995	9.0	49.0	35.6	30.0	685.7	2,608.6	1,652.9	671.2	226.4	26.1	11.2	16.7	6,048
1996	34.4	110.3	116.4	93.6	245.0	796.1	1,638.2	863.5	245.5	25.8	6.0	24.3	4,203
1997	38.3	18.9	14.2	33.9	243.8	598.7	735.9	376.3	43.0	0.0	0.0	0.0	2,066
1998	1.6	10.4	8.1	207.2	198.8	448.4	465.0	89.1	30.8	0.0	0.0	0.0	1,470
1999	12.4	83.7	207.0	157.4	271.5	642.5	861.3	842.6	597.0	61.3	24.0	35.7	3,808
2000	24.1	215.3	423.8	395.9	443.1	728.0	828.0	679.3	169.0	40.7	39.2	135.1	4,120
2001	22.1	253.1	452.3	365.6	761.1	1,388.3	1,154.1	829.1	315.0	34.2	13.1	27.8	5,605
2002	11.2	73.8	243.2	215.8	472.2	2,446.1	2,026.3	913.6	530.0	125.7	30.1	78.9	7,184
2003	28.2	6.8	74.9	189.6	322.2	611.3	848.4	169.3	8.7	0.0	19.5	7.8	2,258
2004	0.0	46.0	324.1	350.7	546.3	567.0	784.9	64.4	11.3	0.0	0.1	0.0	2,695
2005	0.0	0.0	101.8	128.7	401.1	846.3	1,356.4	764.6	76.0	1.2	0.0	2.3	3,684
2006	5.8	168.2	817.9	644.3	565.7	1,986.0	3,578.8	737.5	47.4	6.2	0.0	0.0	8,552
2007	0.0	451.7	276.8	333.4	330.0	636.2	871.3	439.0	38.0	22.8	62.4	63.0	3,565
2008	40.4	169.8	258.2	257.5	457.1	601.2	783.4	657.2	223.6	133.5	84.6	139.2	3,799
2009	33.5	93.5	312.0	464.7	332.2	461.0	738.5	386.2	17.7	18.5	5.6	3.8	2,865
2010	31.3	8.9	0.0	0.0	463.1	816.2	851.2	696.3	140.6	11.3	9.6	198.3	3,220
2011	114.5	476.0	550.4	635.6	1,999.7	3,155.0	3,158.7	805.0	98.7	0.0	0.0	0.0	10,879
2012	141.2	244.4	451.8	342.1	421.2	641.4	660.8	272.8	224.4	38.0	15.1	25.6	3,338
Max	141.2	476.0	908.0	667.1	1,999.7	3,155.0	3,967.3	1,255.3	912.1	176.7	84.6	198.3	10,879
Min	0.0	0.0	0.0	0.0	53.0	264.9	214.2	33.7	8.7	0.0	0.0	0.0	1,103
Mean	24.1	94.9	315.3	258.5	438.9	973.1	1,265.5	551.0	197.6	38.0	15.1	25.6	4,191

Table C.16 Monthly mean observed runoff of C.2 station

Year	Monthly mean runoff (MCM/month)												Annual (MCM)
	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	
1979	1,606	1,655	2,130	1,737	1,972	2,163	2,203	1,673	1,298	618	447	552	16,973
1980	524	984	1,738	2,101	3,128	4,924	9,006	3,152	1,255	764	941	1,225	30,611
1981	1,393	1,670	2,103	2,108	4,126	3,699	2,529	2,993	1,753	921	1,062	1,516	25,938
1982	1,459	1,251	1,056	1,243	1,569	2,637	3,672	2,322	1,192	878	1,142	1,418	19,906
1983	1,526	1,402	1,041	1,017	1,623	2,760	4,631	4,747	1,872	765	1,076	1,536	23,847
1984	1,376	1,169	1,465	1,082	1,375	2,420	2,950	2,335	1,249	768	1,036	1,520	18,795
1985	1,426	1,215	1,051	1,336	1,737	2,613	4,054	4,306	2,423	721	1,042	1,463	23,334
1986	1,372	2,307	2,244	1,721	1,777	2,332	1,984	1,828	1,280	540	1,121	1,460	19,946
1987	1,353	1,147	999	850	1,386	2,609	3,570	1,999	1,264	501	684	1,285	17,341
1988	1,047	1,370	1,450	1,448	1,493	2,132	3,211	2,496	1,239	730	841	1,190	18,956
1989	1,355	1,315	1,891	969	1,300	1,708	2,267	1,921	1,164	583	671	1,303	16,314
1990	1,221	1,358	2,367	1,274	1,240	2,053	2,251	1,602	1,247	632	663	978	16,630
1991	966	662	566	448	1,528	3,026	2,462	1,527	1,029	527	600	735	13,838
1992	728	674	374	291	1,620	1,103	2,603	1,508	1,130	543	591	855	12,140
1993	848	866	1,039	682	975	1,893	1,424	890	682	284	334	432	9,767
1994	266	889	2,615	2,142	2,438	5,383	4,873	1,492	1,324	595	809	1,179	24,946
1995	1,209	1,306	1,335	1,341	3,461	7,635	9,761	4,335	1,773	931	1,272	1,846	36,738
1996	1,740	2,148	2,306	1,586	2,369	4,118	7,208	5,268	2,140	793	1,087	1,392	31,833
1997	1,418	1,332	975	1,005	1,290	2,039	2,632	1,349	1,052	546	770	1,073	15,225
1998	1,162	873	482	1,203	1,124	1,556	2,046	1,102	668	370	507	530	11,039
1999	580	1,458	1,622	879	1,435	3,009	4,825	4,946	1,646	725	1,112	1,290	24,016
2000	1,068	1,777	2,040	1,934	1,874	3,709	4,630	3,228	1,150	979	1,130	1,439	25,068
2001	1,177	1,860	1,820	1,487	3,299	3,938	4,850	3,467	1,437	895	1,008	1,402	26,777
2002	1,315	1,311	1,265	1,271	1,953	6,092	7,936	5,143	2,390	1,280	1,426	1,681	32,887
2003	1,138	1,460	1,637	1,685	1,962	2,874	2,981	1,400	899	727	903	908	18,292
2004	855	977	1,835	1,922	2,573	2,656	2,847	1,089	850	824	782	865	18,181
2005	961	953	1,150	1,145	1,466	3,146	3,902	2,147	1,021	1,051	968	1,003	18,826
2006	873	1,538	2,608	2,649	2,457	5,220	12,377	4,943	1,442	1,316	1,237	1,290	38,305
2007	1,230	2,454	1,823	2,212	1,997	3,246	4,690	2,305	1,163	1,178	1,153	1,116	24,733
2008	1,395	1,712	1,562	1,645	2,100	3,217	4,624	4,766	1,407	1,262	1,268	1,394	26,213
2009	1,258	1,257	1,398	1,765	1,390	2,193	4,213	1,868	1,080	1,104	975	968	18,915
2010	705	601	542	553	2,598	4,266	5,457	4,254	1,386	1,351	1,366	1,621	25,146
2011	1,003	2,262	2,892	3,226	5,442	9,459	11,584	5,950	2,351	2,941	3,190	2,661	51,958
2012	1,566	1,696	1,843	1,439	1,471	3,742	2,841	1,203	1,172	868	1,007	1,246	18,528
Max	1,740	2,454	2,892	3,226	5,442	9,459	12,377	5,950	2,423	2,941	3,190	2,661	51,958
Min	266	601	374	291	975	1,103	1,424	890	668	284	334	432	9,767
Mean	1,150	1,380	1,567	1,453	2,045	3,399	4,503	2,810	1,366	868	1,007	1,246	22,705

Table C.17 Summary of the goodness of fit test in model calibration

Year	Statistic infernces	N.1	N.13A	Inflow	N.12A	N.60	N.5A	N.24
1990	%Diff of Volumn	-1.80	35.93	36.89	-1.61	17.77	-12.99	22.78
	R	0.82	0.74	0.83	0.91	0.68	0.94	0.62
	R^2	0.68	0.54	0.69	0.82	0.47	0.88	0.38
	RMSE	54.98	112.56	102.33	41.40	95.23	56.48	37.89
	SE	37.20	89.05	88.46	37.42	82.48	45.07	37.01
1991	%Diff of Volumn	15.36	42.15	49.49	9.66	16.24	12.44	-27.94
	R	0.86	0.84	0.87	0.97	0.62	0.89	0.76
	R^2	0.75	0.70	0.75	0.93	0.38	0.80	0.58
	RMSE	41.23	87.40	92.25	24.62	62.24	64.81	47.88
	SE	37.12	71.39	74.19	16.76	47.58	59.91	18.56
1992	%Diff of Volumn	63.09	76.35	82.80	-1.01	34.81	32.75	-6.62
	R	0.84	0.75	0.84	0.85	0.59	0.85	0.73
	R^2	0.70	0.56	0.71	0.73	0.34	0.72	0.53
	RMSE	68.93	134.43	129.42	50.59	71.10	79.50	16.11
	SE	57.32	113.13	96.44	30.59	51.28	68.18	13.79
1993	%Diff of Volumn	86.23	80.06	74.34	5.41	8.75	21.15	30.45
	R	0.75	0.75	0.79	0.95	0.87	0.86	0.68
	R^2	0.56	0.56	0.62	0.90	0.76	0.74	0.47
	RMSE	106.04	164.59	134.02	35.42	52.76	71.87	19.74
	SE	90.75	137.96	110.12	28.13	38.66	64.52	16.26
1994	%Diff of Volumn	17.29	0.69	17.22	-3.42	6.28	4.82	-29.52
	R	0.93	0.93	0.92	0.95	0.81	0.97	0.82
	R^2	0.87	0.86	0.85	0.90	0.66	0.94	0.67
	RMSE	94.68	211.59	158.53	38.08	76.84	54.73	35.33
	SE	88.53	146.42	139.48	32.87	61.90	53.51	18.54
1995	%Diff of Volumn	7.39	-10.91	5.27	-7.70	-10.82	-8.52	-23.04
	R	0.91	0.89	0.91	0.77	0.89	0.98	0.85
	R^2	0.83	0.80	0.82	0.59	0.79	0.97	0.72
	RMSE	121.38	312.13	216.61	203.25	157.87	86.56	29.90
	SE	100.99	180.59	156.50	93.02	90.55	66.90	16.33
1996	%Diff of Volumn	16.53	-8.77	16.35	4.93	-5.64	-6.86	-37.02
	R	0.84	0.83	0.85	0.95	0.87	0.98	0.78
	R^2	0.70	0.69	0.72	0.90	0.76	0.96	0.61
	RMSE	88.21	199.88	131.28	42.97	94.58	57.69	51.79
	SE	84.62	125.77	124.19	38.56	87.40	52.05	18.70
1997	%Diff of Volumn	33.28	2.70	21.37	3.86	0.60	0.03	-11.39
	R	0.94	0.91	0.93	0.95	0.80	0.94	0.81
	R^2	0.89	0.83	0.87	0.90	0.64	0.88	0.66
	RMSE	64.54	142.91	89.97	32.39	58.54	41.99	22.10
	SE	53.30	108.48	84.49	30.15	50.41	41.67	11.85
1998	%Diff of Volumn	48.61	53.60	72.40	13.31	25.82	19.43	-14.13
	R	0.90	0.87	0.93	0.91	0.69	0.83	0.69
	R^2	0.81	0.75	0.87	0.83	0.48	0.69	0.48
	RMSE	59.31	142.92	119.79	34.77	63.44	56.16	21.29
	SE	50.63	121.61	77.76	27.51	46.51	44.48	14.53

Table C.17 Summary of the goodness of fit test in model calibration (continued)

Year	Statistic infernces	N.1	N.13A	Inflow	N.12A	N.60	N.5A	N.24
1999	%Diff of Volumn	2.49	0.59	33.63	6.86	26.55	0.92	-25.64
	R	0.94	0.92	0.93	0.96	0.84	0.95	0.70
	R^2	0.88	0.86	0.87	0.92	0.71	0.91	0.49
	RMSE	64.90	178.39	126.93	39.02	98.60	49.76	27.05
	SE	52.48	119.57	106.12	36.42	57.45	46.30	15.90
2000	%Diff of Volumn	19.96	5.44	25.73	5.66	1.24	-2.41	-36.54
	R	0.80	0.80	0.80	0.97	0.76	0.92	0.72
	R^2	0.64	0.65	0.65	0.94	0.58	0.84	0.51
	RMSE	92.91	207.93	157.72	29.92	72.46	53.43	54.95
	SE	85.09	174.65	148.83	25.58	54.34	52.23	20.69
2001	%Diff of Volumn	-2.13	-15.96	-0.02	-4.83	-9.82	-7.89	-34.57
	R	0.95	0.93	0.92	0.96	0.92	0.98	0.69
	R^2	0.91	0.86	0.85	0.92	0.85	0.96	0.48
	RMSE	58.16	232.90	136.30	58.45	95.61	54.10	30.81
	SE	53.15	140.55	121.68	47.60	69.87	44.75	13.54
2002	%Diff of Volumn	-8.00	-21.45	10.41	-3.65	-8.13	-2.61	-40.36
	R	0.86	0.88	0.86	0.95	0.82	0.98	0.87
	R^2	0.75	0.77	0.74	0.91	0.68	0.96	0.77
	RMSE	89.93	262.10	125.95	39.28	93.99	48.45	70.03
	SE	63.98	132.16	116.85	32.80	46.34	47.36	18.26
2003	%Diff of Volumn	-1.36	-11.42	0.50	10.69	-8.53	-4.73	-18.03
	R	0.95	0.94	0.95	0.90	0.73	0.94	0.76
	R^2	0.90	0.88	0.89	0.82	0.54	0.89	0.58
	RMSE	39.92	149.50	76.89	43.18	79.78	43.75	20.10
	SE	35.74	86.22	74.76	34.64	44.02	42.20	13.25
2004	%Diff of Volumn	8.51	-3.20	-7.09	8.94	6.20	-6.41	-24.78
	R	0.94	0.93	0.94	0.95	0.86	0.96	0.78
	R^2	0.89	0.86	0.88	0.91	0.74	0.93	0.61
	RMSE	63.75	154.25	106.91	38.17	63.11	44.15	27.47
	SE	58.34	113.91	95.59	32.63	46.59	40.90	15.85
2005	%Diff of Volumn	25.57	7.90	7.51	16.21	10.10	-6.48	-10.12
	R	0.92	0.92	0.92	0.94	0.77	0.96	0.77
	R^2	0.85	0.84	0.85	0.88	0.60	0.93	0.60
	RMSE	69.48	147.48	114.79	46.65	73.90	38.87	21.63
	SE	64.60	128.98	113.87	34.81	39.96	35.35	13.07
2006	%Diff of Volumn	-25.27	-9.40	-7.31	25.11	2.27	12.62	-24.58
	R	0.91	0.85	0.85	0.91	0.81	0.98	0.86
	R^2	0.83	0.72	0.72	0.82	0.66	0.96	0.74
	RMSE	117.18	231.13	175.72	65.00	96.83	65.83	23.90
	SE	64.25	164.26	164.33	43.40	58.85	51.96	14.85
2007	%Diff of Volumn	0.05	5.78	6.49	20.13	-8.79	-0.18	-28.02
	R	0.81	0.84	0.84	0.87	0.73	0.96	0.85
	R^2	0.66	0.70	0.70	0.76	0.53	0.91	0.73
	RMSE	68.69	129.06	114.02	52.69	60.26	46.26	40.89
	SE	65.13	118.75	113.43	35.87	43.42	43.53	22.72

Appendix D

Existing and adaptive dam operation model

Appendix D

Existing and adaptive dam operation models

D.1 Existing reservoir operation model

D.1.1 The release – storage ratio reservoir operation model component

The dam operation development by the release – storage ratio (RSR) method composes 4 components i.e., 1) reservoir operation model; 2) water release decision making module by tree probability classification process; 3) water demand decision making module; 4) water network balance model (see detail in Appendix F).

D.1.2 Reservoir water balance concept

The reservoir water balance was proposed and applied in this study to calculate the storage of Sirikit Dam by the following equation:

$$S_t = S_{t-1} + I_t + R_t - O_t - E_t \tag{1}$$

where S_t is the storage in the present period , MCM , S_{t-1} is the storage in previous period , MCM, I_t is the inflow in this period , MCM, R_t is the rainfall in the present period, $R_t = (1 - C) \times r_t \times A(S_t)/1000$, MCM, C is the runoff coefficient that was assumed as 0.75. r_t is the rainfall at the present period, mm/month. $A(St)$ is the surface area of the reservoir in the present period that depend on the water storage at the present period, Km^2. O_t is the release and spillage in the present period , MCM, E_t is the evaporation at the present period , $Et = 0.78 \times E_p \times A(S_t)/1000$, MCM, E_p is evaporation that calculated from Penman – Montein equation.

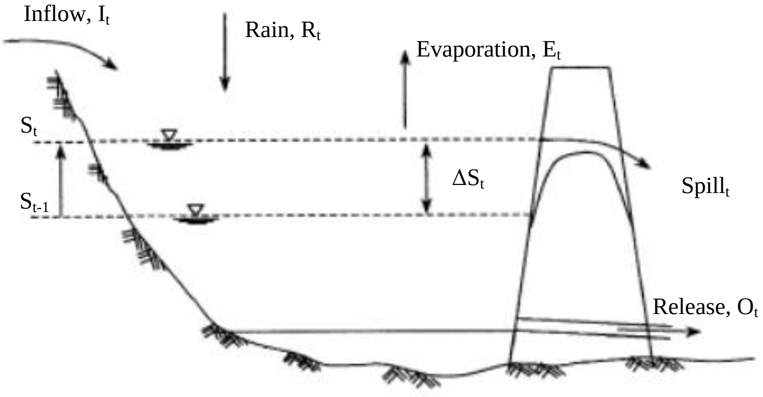


Figure D.1 The schematic of reservoir water balance

D.1.3 Reservoir operating criteria

1) Minimum water level or minimum pool level is defined to reserve the water storage for trapping the suspended sediment. For the reservoir management will be allow the water level of reservoir lower than the minimum level in the case release for domestic use propose only. However, at the minimum water level, the reservoir can release in the normal condition that the minimum water storage will be equal to the lowest outlet level, or in the generated electricity reservoir will define the minimum storage by considering the turbine managing efficiency.

2) Normal high water level or normal pool level is defined for controlling the reservoir storage between minimum water level and normal water level has the water sufficiently to manage the inflow to reservoir in each year. Furthermore, it can be responded the water use activities according to the objective of the reservoir. On the other hand, the normal high water level is the full water storage level as designing the equal to the crest of spillway. Thus, if the runoff flows to reservoir higher than this level, it will drain to the spillway. However, in the case of spillway has the controlling gate can be store more water but it should have the restrict release measure.

3) Minimum Water Level or Maximum Flood Water Level is the water level which allows to happen in the case of the designed flood for spillway flows to the reservoir, and then gain the water level higher under the designed open-close gate of spillway conditions. While the reservoir still has the freeboard level enough to protect to water spillage the crest of dam.

4) The reservoir operation rule curve is defined for the desired water storage according to the 1-year reservoir management plan. The concept is: the flood season, the water storage will be controlled to low level as possible for receive the flood water flow to the reservoir and protect the downstream flood. After the flood period, The reservoir should be kept high water level to prepare the release for water use activities. However, the release rule will attempt to adjust to increase or reduce the water storage close to the rule curve.

D.1.4 The existing reservoir operation model development

The existing reservoir operation development includes the reservoir operation model, the release decision making rules, the water demand decision making module and the water network balance model development. The detail of existing reservoir operation model follows as:

D.1.4.1 Reservoir operation model development

The reservoir operation model is to balance the storage in the reservoir by using reservoir water balance equation follows as:

1) Collect and enter the input variables into the reservoir operation model included rainfall, maximum and minimum temperature, relative humidity, initial storage, inflow and the reservoir characteristics.

2) Collect the historical cultivated area and basically information for water demand estimation in Phisanulok and Chao Phraya irrigation Projects

3) Enter the input variables into the reservoir operation model included rainfall, maximum and minimum temperature, relative humidity, initial storage and inflow based on monthly basis.

4) Assign the reservoir characteristics such as height – volume – area curve, crest of spillway, maximum storage level, normal storage level, dead storage level and reservoir rule curve.

5) Develop the release rules as the water release making decision module by calculating the release – storage ratio for general and flood control operation.

6) Develop the water demand decision making module by using probability decision tree method to classify from the storage at the end of season and estimate the water demand unit bases on the climate condition.

7) Develop the water network balance model by calibrating and verifying model with the observed runoff and integrate this model to reservoir operation model.

8) Apply the general and flood dam operation model by integrating the release rules, the water demand decision making module, the water demand decision making module and the water network balance module.

9) Assess the impact of climate change on the reservoir water balance, water shortage, spillage and accumulative runoff at the downstream by general and flood control dam operation.

D.1.4.2 Decision trees classification method

A decision tree partitions the input space (also known as the feature or attribute space) of a data set into mutually exclusive regions, each of which is assigned a label, a value, or an action to characterize its data points. The decision tree mechanism is transparent and we can follow a tree structure easily to explain how a decision is made, therefore, the decision tree method has been used extensively in machine learning, expert systems, and multivariate analysis; it is perhaps the most highly developed technique for partitioning sample data into a collection of decision rules.

A decision tree is a tree structure consisting of internal and external nodes connected by branches. An internal node is a decision-making unit that evaluates a decision function to determine which child node to visit next. In contrast, an external node, also known as a leaf or terminal node, has no child nodes and is associated with a label or value that characterizes the given data that lead to its being visited. In general, decision tree is employed as follows. First, we present a datum (usually a vector composed of several attributes or elements) to the starting node (or root node) of the decision tree. Depending on the result of a decision function used by an internal node, the tree will branch to one of the node's children. This is repeated until a terminal node is reached and a label or value is assigned to the given input data. The decision tree classification method follow as: 1) Identify the problems opportunities; 2) Assess the situation : this study focused on the release rule and water demand; 3) Determining success criteria; 4) Identify the interval of probability; 5) Generate alternatives.

D.1.5 Water release decision making module

1) For the general dam operation rule which patternize the release rule bases on the historical data. The release rule can formulate follow as:

1.1) Patternize the release rule of the dam from the effective storage in each water season and each month within the season by using probability decision tree method and classified to be high, normal, dry and very dry water season. The wet season start from Apr 30 and dry season start from Oct 31. The classification of antecedent storage of Sirikit Dam by probability decision trees show as Figure D.4.

1.2) Analyze the release-effective storage ratio (r_i) from the proportion between monthly water release at the present month (O_t) and antecedent effective storage (Se_{t-1}). Thus, the average monthly release-effective storage ratio was grouped into the water season and monthly antecedent effective storage level. The amount of water release in the present month (R_t) can be calculated by taking the antecedent effective storage (Se_{t-1}) multiply with this release-effective storage ratio (r_i). The release – storage ratio of Sirikit Dam shows in Table D.2. The release-effective storage ratio (r_i) was calculated by the following equation:

$$r_i = \frac{O_t}{Se_{t-1}} \qquad (2)$$

where r_i is the release-effective storage ratio, month^{-1}, O_t is monthly water release at the present month, MCM/month and Se_{t-1} is the average monthly effective storage at previous month, MCM.

1.3) Calibrate the release rule by simulating the reservoir operation in year 1979 – 2011.

1.4) Verify the release rule by simulating the reservoir operation in year 1979 – 2011.

2) For the flood dam operation rule, the proportion of water release and effective storage of the water management plan in year 2012 was used as the flood water operation rule.

For water release pattern, the dam effective water storage at the end of previous season as the initial water season was used to set the water release rule. It was found that water release pattern in the wet season can be classified into 4 water seasons based on the probability (P) of antecedent effective storage (shown as Figure D.2) such as high ($Seff_{t-1}$ > 2,991 MCM), normal (1,381 MCM > $Seff_{t-1}$ >= 2,991 MCM), dry (648 MCM > $Seff_{t-1}$ >= 1,381 MCM) and very dry ($Seff_{t-1}$ < 648 MCM) water season.

For the dry season can be classified into 4 water seasons also such as high ($Seff_{t-1}$ > 5,767 MCM), normal (3,826 MCM > $Seff_{t-1}$ >= 5,767 MCM), dry (2,033 MCM > $Seff_{t-1}$ >= 3,826 MCM) and very dry ($Seff_{t-1}$ < 2,033 MCM) water season. During the season, the monthly antecedent effective storage in each season can be separated into 5 levels based on the probability tree of antecedent effective storage ($Seff_{t-1}$) classification such as higher (P = 0.90 – 1.00), high (P = 0.80 – 0.90), medium (P = 0.30 – 0.80), low (P = 0.10 – 0.30) and lower level (P = 0.00 – 0.10), respectively. The figure of the monthly effective storage in each level is shown in Figure D.4. The release-effective storage ratio was shown as Table D.2.

Table D.1 The criteria of water season classification for antecedent effective storage

Season	Water season	Probability	Effective Storage (MCM)
Wet Season	High	0.75 - 1.00	x > 2,991
	Normal	0.30 - 0.75	1,381 > x >= 2,991
	Dry	0.10 - 0.30	648 > x >= 1,381
	Very Dry	0 - 0.10	x < 648
Dry Season	High	0.75 - 1.00	x > 5,767
	Normal	0.30 - 0.75	3,826 > x >= 5,767
	Dry	0.10 - 0.30	2,033 > x >= 3,826
	Very Dry	0 - 0.10	x < 2,033

The proposed dam operation pattern based on probability decision tree method can be calibrated and verified by comparing the observed release data which recorded by EGAT with the computed release from the release pattern derived. The check and varification periods are the year 1987 – 1996 and year 1997 – 2011 respectively. The correlation (R^2) and the root mean square error of water release of Sirikit dam in check period are found to be good as 0.74 and 166 MCM, respectively. The correlation (R^2) and the root mean square error of release in verification period are found to be good as 0.80 and 145 MCM, respectively. The result has shown that proposed decision tree method can patternize water release under general dam operation rule reasonably. This pattern was further used in the dam water balance study to assess the impact of the climate change on dam operation. For the release pattern under flood dam operation rule, the proportion of water release and effective storage in the year 2012 was used as the flood water operation pattern. However since this study focused Sirikit dam operation cope with the water demand in Nan Basin, thus Bhumibol dam operation will not be considered in the dam release study in this study.

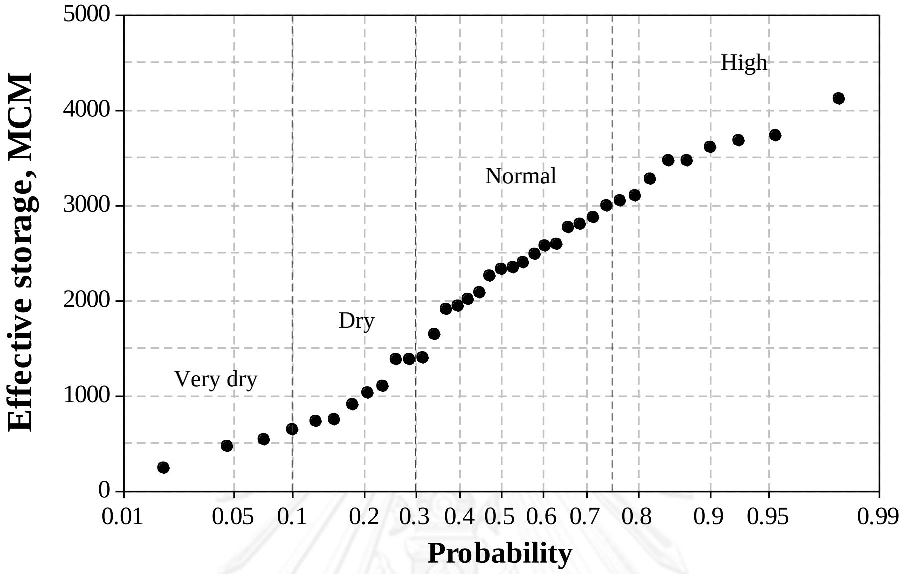


Figure D.2 Probability of the monthly antecedent effective storage of Sirikit Dam in wet season

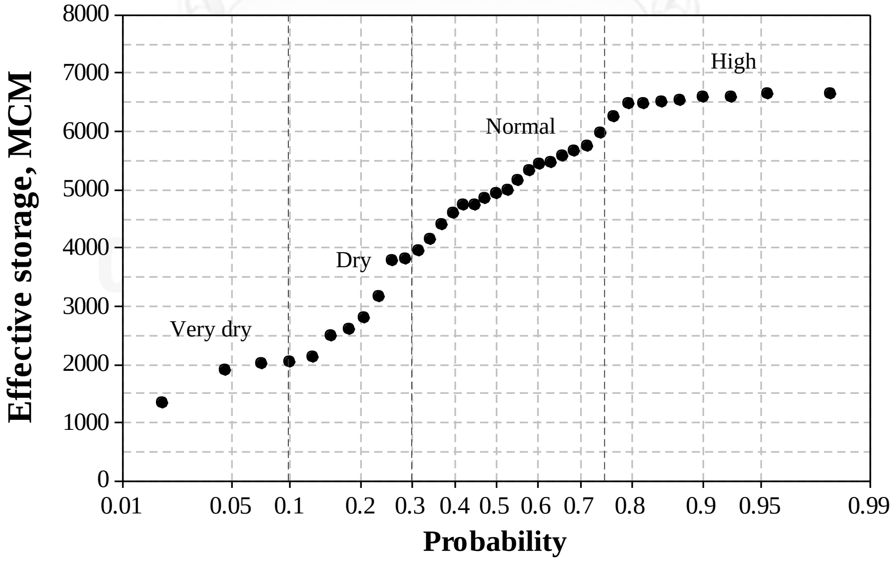


Figure D.3 Probability of the monthly antecedent effective storage of Sirikit Dam in dry season

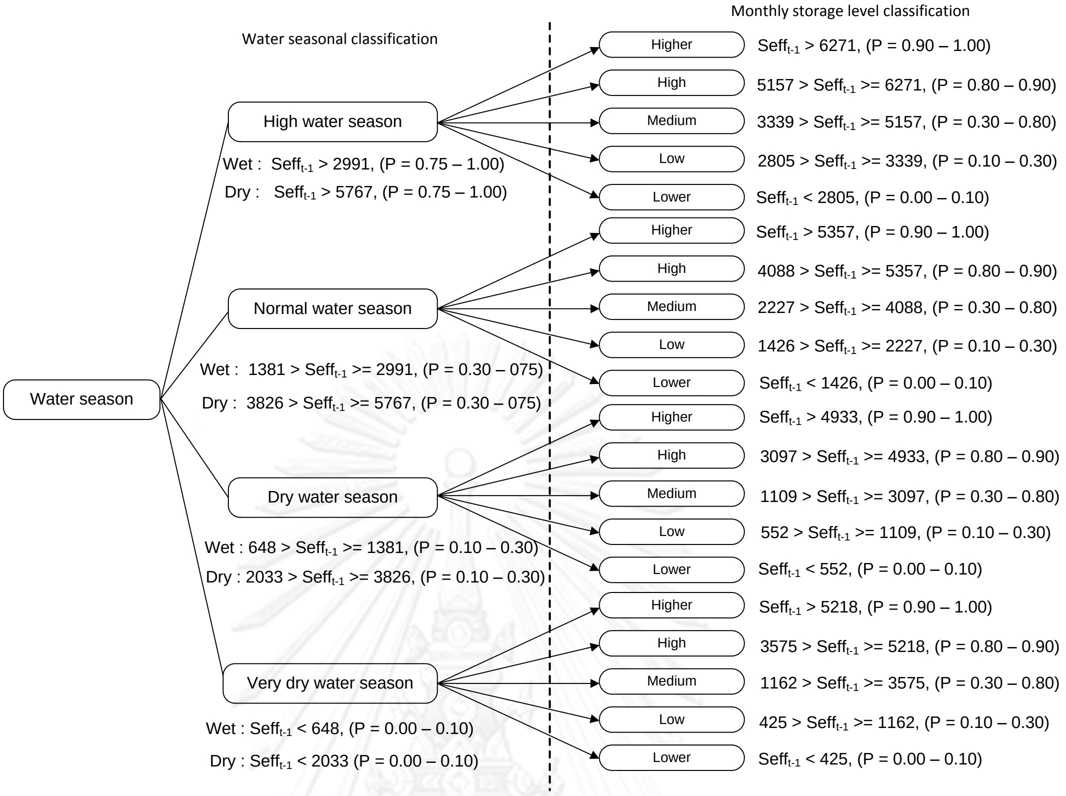
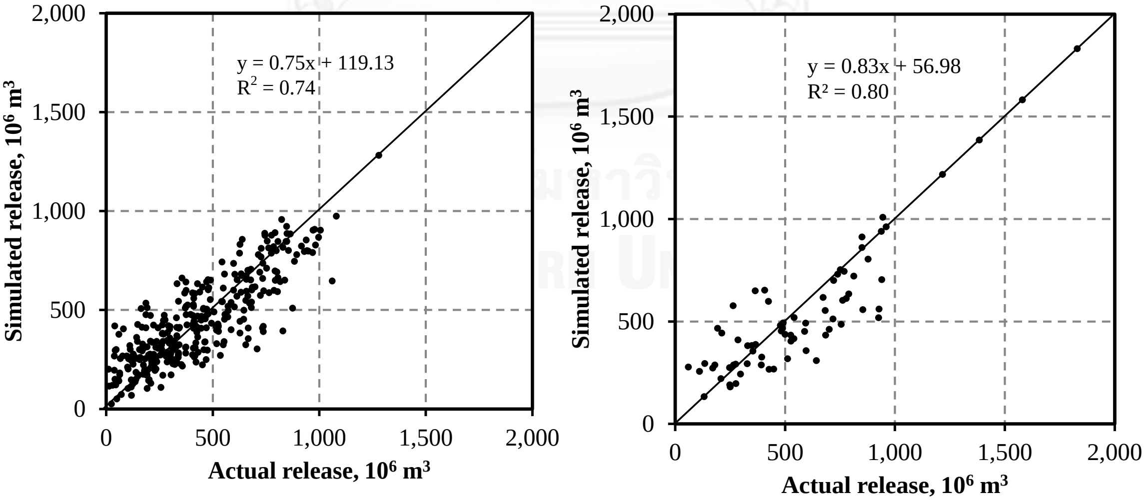


Figure D.4 The classification of antecedent storage of Sirikit Dam by probability decision trees



(a) Calibration period (1979 – 2006) (b) Validation period (2007 – 2011)

Figure D.5 The comparison of actual and simulated water release of Sirikit Dam

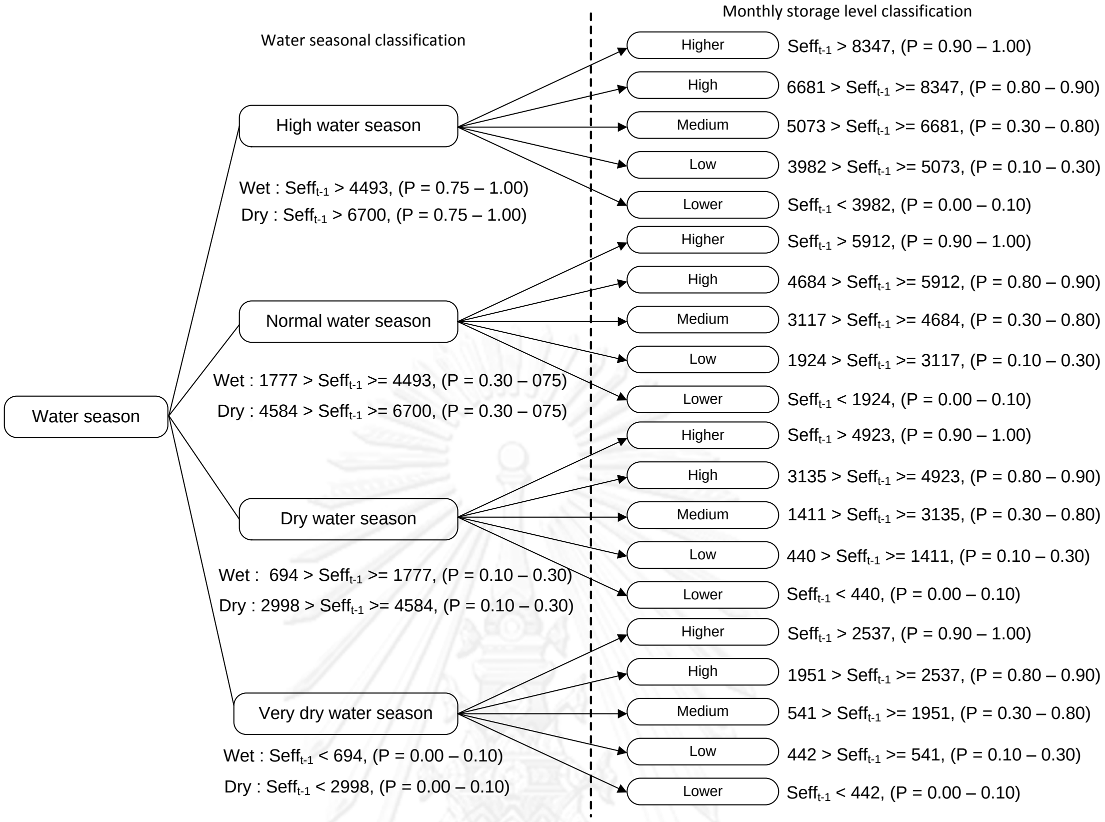


Figure D.6 The classification of antecedent storage of Bhumibol Dam by probability decision trees

Table D.2 The release – storage ratio of Sirikit Dam

Dam operation rule	Water season	Monthly level	Release - storage ratio (month^{-1})											
			May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
1. General	High	higher	0.21	0.24	0.08	0.17	0.21	0.11	0.06	0.06	0.08	0.13	0.17	0.20
		high	0.21	0.24	0.08	0.17	0.21	0.04	0.08	0.10	0.10	0.13	0.17	0.20
		medium	0.21	0.24	0.08	0.17	0.05	0.06	0.12	0.07	0.10	0.14	0.19	0.20
		low	0.15	0.15	0.16	0.17	0.09	0.06	0.12	0.07	0.10	0.21	0.25	0.24
		lower	0.34	0.26	0.22	0.20	0.09	0.06	0.12	0.07	0.10	0.21	0.25	0.30
	Normal	higher	0.23	0.17	0.15	0.25	0.09	0.07	0.07	0.09	0.12	0.15	0.19	0.26
		high	0.23	0.17	0.15	0.25	0.09	0.05	0.05	0.07	0.11	0.15	0.19	0.26
		medium	0.23	0.17	0.15	0.13	0.08	0.07	0.13	0.10	0.14	0.18	0.24	0.26
		low	0.30	0.21	0.28	0.26	0.14	0.13	0.25	0.19	0.09	0.20	0.32	0.34
		lower	0.33	0.29	0.33	0.49	0.11	0.13	0.25	0.19	0.15	0.14	0.24	0.40
	Dry	higher	0.26	0.12	0.16	0.15	0.06	0.00	0.03	0.06	0.10	0.16	0.18	0.19
		high	0.26	0.12	0.16	0.15	0.06	0.05	0.04	0.05	0.07	0.10	0.18	0.19
		medium	0.26	0.12	0.16	0.15	0.13	0.11	0.18	0.06	0.13	0.25	0.31	0.22
		low	0.26	0.38	0.32	0.50	0.19	0.11	0.18	0.19	0.20	0.32	0.31	0.25
		lower	0.58	0.46	0.70	0.60	0.19	0.11	0.18	0.19	0.20	0.32	0.50	0.40
	Very Dry	higher	0.44	0.24	0.15	0.07	0.06	0.03	0.07	0.05	0.06	0.11	0.16	0.17
		high	0.44	0.24	0.15	0.07	0.06	0.07	0.04	0.05	0.08	0.11	0.16	0.17
		medium	0.44	0.24	0.15	0.07	0.09	0.03	0.11	0.09	0.10	0.18	0.30	0.27
		low	0.44	0.24	0.15	0.07	0.05	0.03	0.11	0.09	0.10	0.18	0.30	0.50
		lower	0.42	0.35	0.80	0.06	0.05	0.03	0.11	0.09	0.10	0.18	0.30	0.50
2. Flood			0.18	0.24	0.34	0.40	0.23	0.11	0.11	0.10	0.15	0.20	0.29	0.35

Table D.3 The release – storage ratio of Bhumibol Dam

Dam operation rule	Water season	Monthly level	Release - storage ratio (month^{-1})											
			May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
1. General	High	higher	0.12	0.10	0.17	0.05	0.02	0.07	0.07	0.09	0.13	0.10	0.13	0.12
		high	0.12	0.10	0.17	0.05	0.02	0.01	0.03	0.06	0.09	0.13	0.13	0.12
		medium	0.12	0.10	0.17	0.05	0.02	0.05	0.06	0.06	0.08	0.12	0.16	0.13
		low	0.12	0.10	0.08	0.09	0.05	0.03	0.06	0.06	0.08	0.12	0.21	0.17
		lower	0.12	0.16	0.16	0.12	0.07	0.05	0.06	0.06	0.08	0.12	0.21	0.30
	Normal	higher	0.14	0.09	0.11	0.09	0.12	0.12	0.00	0.04	0.05	0.09	0.13	0.13
		high	0.14	0.09	0.02	0.10	0.04	0.04	0.06	0.09	0.10	0.12	0.18	0.13
		medium	0.14	0.09	0.11	0.09	0.05	0.03	0.07	0.05	0.12	0.17	0.21	0.20
		low	0.18	0.13	0.12	0.15	0.08	0.06	0.07	0.05	0.12	0.17	0.26	0.25
		lower	0.26	0.19	0.24	0.25	0.14	0.16	0.07	0.05	0.12	0.17	0.26	0.33
	Dry	higher	0.23	0.03	0.05	0.01	0.01	0.01	0.09	0.01	0.04	0.11	0.16	0.14
		high	0.23	0.03	0.05	0.01	0.01	0.01	0.09	0.07	0.06	0.11	0.21	0.14
		medium	0.23	0.03	0.05	0.01	0.03	0.03	0.07	0.20	0.14	0.18	0.25	0.31
		low	0.44	0.32	0.25	0.15	0.05	0.17	0.07	0.20	0.14	0.18	0.25	0.35
		lower	0.44	0.53	0.76	0.49	0.26	0.17	0.07	0.20	0.14	0.18	0.25	0.35
	Very Dry	higher	0.34	0.07	0.06	0.05	0.02	0.02	0.15	0.12	0.15	0.17	0.29	0.35
		high	0.34	0.07	0.06	0.05	0.08	0.02	0.15	0.10	0.15	0.17	0.29	0.35
		medium	0.34	0.07	0.06	0.05	0.08	0.02	0.21	0.10	0.15	0.21	0.29	0.35
		low	0.34	0.07	0.40	0.05	0.08	0.02	0.21	0.10	0.15	0.21	0.29	0.30
		lower	0.10	0.28	0.40	0.57	0.08	0.02	0.21	0.10	0.15	0.21	0.29	0.30
2. Flood			0.10	0.12	0.13	0.13	0.09	0.09	0.08	0.08	0.15	0.18	0.24	0.27

D.1.6 Water demand decision making module

The water demand system is the decision module for determining the crop cultivation area in the downstream irrigation projects. The concept of the water demand system bases on the decision tree classification method. The logic of this system will decide the suitable cultivated area according to the probability of the effective storage at the end of previous season that mean the dam operation will determine the release rules from the residual water budget of the dam. This system is designed into 2 layers decisions included 1) identifying water season at the present period and 2) identifying monthly level in water season.

The water demand unit (MCM/month/rai) was calculated as the default values. Thus, the water demand unit was calculated under climate condition that included present, near future and far future period. Hence, the variables which effect to water demand are the different effective rainfall and evapotranspiration that concern as the water demand rate with climate condition. The cropping pattern in this study was assumed as the present period, the farmer start to cultivate in wet season at the mid of May to mid of November and dry season at the early of December to mid of March. Due to the cultivating behavior of farmers in Thailand do not cultivate the same time, the water demand calculation also consider the percentage of incremental area as the one of factors in the water demand estimation. This percentage of incremental area was adopted from the interview and some recorded cultivation area by RIO3.

During the program running, the water demand system will select cultivated area by decision tree classification that will be taken it to multiply with the water demand rate. While the water demand will be incorporated to water balance model in the same time. The advantage of this system is the reservoir operation can adjust the release following the water demand under the present month by consider the water budget in the previous month.

However the limitation of this system bases on the historical cultivation and the limitation of irrigation project area. If there are some of driving planting factors or any policies to induce the farmers plant rice more than 2 crops per year, this water demand system will not take it to consider. Due to this study attempted to adjust the dam operation responding to climate change only. The classification of cultivated area for Phitsanulok and Chao Phraya Irrigation Projects show as Table D.4 and D.5. The probability decision trees of crop cultivation area show as Figure D.7 and D.8. The water demand estimation can follow as:

1) Collect the historical cultivated area in Phisanulok and Chao Phraya irrigation Projects (year 1985 - 2008) from Irrigation Office 3, Royal Irrigation Department (RIO3).

2) Calculate the irrigation water demand rate (MCM/1,000 rais) from the effective rainfall and evapotranspiration under the climate condition.

3) Classify the cultivated area from the effective storage at the end of season.

4) In the application of the water demand system, first the present water season will be defined by the monthly effective storage at the end of previous season dynamically. Second the water demand system will identify the level of cultivation from the monthly effective storage at the end of previous season also. Finally, the irrigation water demand of Phisanulok Irrigation Project and Great Chao Phraya Project will be estimated from the cultivated area multiply with the monthly water demand rate (MCM/month/rai).

5) Apply the water demand system as the water demand decision making module into the water balance model as the input variables in the general, flood and adjusted dam operation.

The classification of crop cultivation area for Phitsanulok and Great Chao Phraya Project Irrigation Project show as Table D.4 and D.5. The probability decision trees of cultivated area of Phitsanulok and Chao Phraya Irrigation Project show as Figure D.7 and D.8. For the classification of crop cultivation area can follow as:

- Create the probability of effective storage at the end of season (S_s) for classifying the water season to be high, normal, dry and very dry water season same as the release patternization.

- Under the cultivated area in each water season, classify the cultivated area (A_c) in each water season by the probability decision tree classification method and then set the level of cultivation as high intensity (P = 0.67 – 1.00), medium intensity (P = 0.33 – 0.67) and low intensity (P = 0.00 – 0.33).

- Average the cultivated areas matching with the level of cultivation.

Table D.4 The classification of crop cultivation area for Phitsanulok Irrigation Projects

Season	Water season	Probability	Effective storage at the end of previous season (Mm^3)	Monthly Level	Monthly effective storage (Mm^3)	Cultivated area$^{1/}$ (rais)
Wet Season	High	0.75 - 1.00	$Seff_{s-1} > 2,991$	High	$Seff_t > 3,609$	606,274
				Medium	$3,107 > Seff_t >= 3,609$	565,778
				Low	$Seff_t <= 3,107$	503,458
	Normal	0.30 - 0.75	$1,381 > Seff_{s-1} >= 2,991$	High	$Seff_t > 2,483$	648,294
				Medium	$1,955 > Seff_t >= 2,483$	566,650
				Low	$Seff_t <= 1,955$	519,358
	Dry$^{2/}$	0.10 - 0.30	$648 > Seff_{s-1} >= 1,381$	High	$Seff_t > 1,042$	624,574
				Medium	$737 > Seff_t >= 1,042$	560,743
				Low	$Seff_t <= 737$	526,757
	Very Dry$^{2/}$	0 - 0.10	$Seff_{s-1} <= 648$	High	$Seff_t > 480$	624,574
				Medium	$246 > Seff_t >= 480$	519,763
				Low	$Seff_t <= 246$	510,925
Dry Season	High	0.75 - 1.00	$Seff_{s-1} > 5,767$	High	$Seff_t > 6,590$	682,162
				Medium	$6,477 > Seff_t >= 6,590$	544,452
				Low	$Seff_t <= 6,477$	111,156
	Normal	0.30 - 0.75	$3,826 > Seff_{s-1} >= 5,767$	High	$Seff_t > 5,328$	626,670
				Medium	$4,753 > Seff_t >= 5,328$	486,497
				Low	$Seff_t <= 4,753$	122,276
	Dry	0.10 - 0.30	$2,033 > Seff_{s-1} >= 3,826$	High	$Seff_t > 3,173$	598,393
				Medium	$2,512 > Seff_t >= 3,173$	305,525
				Low	$Seff_t <= 2,512$	216,254
	Very Dry	0 - 0.10	$Seff_{s-1} <= 2,033$	High	$Seff_t > 2,008$	234,473
				Medium	$1,916 > Seff_t >= 2,008$	139,215
				Low	$Seff_t <= 1,916$	134,617

Remark : 1/ Cultivated area is the paddy planting area.

Table D.5 The classification of cultivated area for Chao Phraya Irrigation Projects

Season	Water season	Probability	Storage at the end of previous season (MCM)	Monthly level	Monthly storage (MCM)	Rice (rais)	Crop (rais)
Wet Season	High	0.75 - 1.00	$Seff_{s-1} > 7,535$	High	$Seff_t > 8,726$	6,013,172	40,348
				Medium	$8,204 > Seff_t >= 8,726$	4,959,907	29,007
				Low	$Seff_t < 8,204$	4,705,240	22,784
	Normal	0.30 - 0.75	$3,728 > Seff_{s-1} >= 7,535$	High	$Seff_t > 6,509$	6,224,301	41,028
				Medium	$4,779 > Seff_t >= 6,509$	5,683,581	37,016
				Low	$Seff_t < 4,779$	4,696,820	22,643
	Dry[2/]	0.10 - 0.30	$1,394 > Seff_{s-1} >= 3,728$	High	$Seff_t > 2,869$	6,063,196	69,392
				Medium	$1,923 > Seff_t >= 2,869$	5,388,860	38,417
				Low	$Seff_t < 1,923$	4,498,671	25,066
	Very Dry[2/]	0 - 0.10	$Seff_{s-1} < 1,394$	High	$Seff_t > 1,130$	5,623,723	37,069
				Medium	$856 > Seff_t >= 1,130$	5,265,075	33,347
				Low	$Seff_t < 856$	4,757,635	25,369
Dry Season	High	0.75 - 1.00	$Seff_{s-1} > 12,028$	High	$Seff_t > 14,734$	4,649,456	30,357
				Medium	$13,158 > Seff_t >= 14,734$	3,539,117	21,288
				Low	$Seff_t < 13,158$	1,649,177	13,312
	Normal	0.30 - 0.75	$8,720 > Seff_{s-1} >= 12,028$	High	$Seff_t > 10,993$	5,169,949	65,781
				Medium	$10,106 > Seff_t >= 10,993$	3,276,745	24,559
				Low	$Seff_t < 10,106$	1,336,388	10,787
	Dry	0.10 - 0.30	$5,136 > Seff_{s-1} >= 8,720$	High	$Seff_t > 8,152$	4,677,382	66,479
				Medium	$5,518 > Seff_t >= 8,152$	2,745,440	22,160
				Low	$Seff_t < 5,518$	2,050,005	16,547
	Very Dry	0 - 0.10	$Seff_{s-1} < 5,136$	High	$Seff_t > 4,850$	3,279,054	32,827
				Medium	$3,374 > Seff_t >= 4,850$	2,060,101	16,628
				Low	$Seff_t < 3,374$	1,761,507	14,218

Remark : Storage at the end of previous season and monthly storage were determined from Sirikit and Bhumibol dam

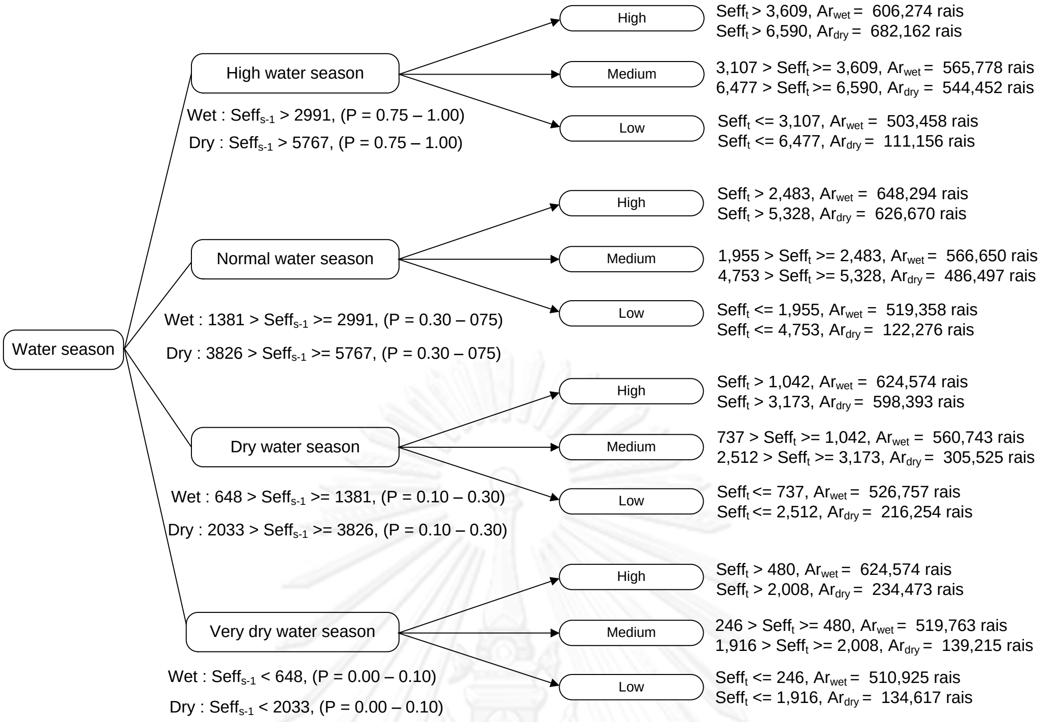


Figure D.7 The probability decision trees of cultivated area of Phitsanulok Irrigation Project

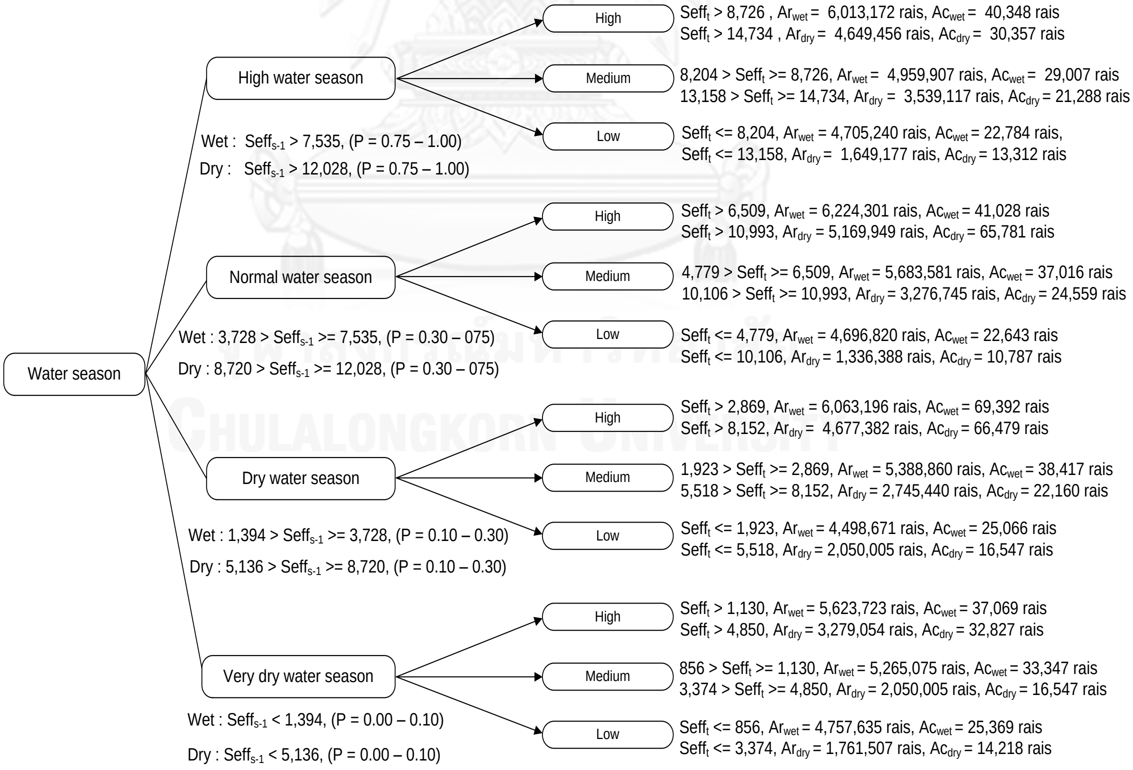


Figure D.8 The probability decision trees of cultivated area of Chao Phraya Irrigation Project

D.1.7 Reservoir operation simulation procedures

The reservoir operation model is to balance the storage in the reservoir by using reservoir water balance equation follows as:

1) Enter the input variables into the reservoir operation model included rainfall, maximum and minimum temperature, relative humidity, initial storage and inflow based on monthly basis.

2) Assign the reservoir characteristics such as height – volume – area curve, crest of spillway, maximum storage level, normal storage level, dead storage level and reservoir rule curve.

3) Apply the reservoir water balance equation to calculate the present storage (S_t). The reservoir water balance was proposed and applied in this study to calculate the storage of Sirikit Dam by the following Eq.(1)

4) Apply the dam operation rule into reservoir operation model for the release decision making module. The dam operation rule in this study included 4 release decision making rules such as general, flood, adjusted general and adaptive dam operation. In the application of these rules can be separate the how to use rules into 2 methods.

For the general, flood and adjusted general dam operation rules, the release (O_t) can be calculate by the following equation:

$$O_t = ri \times Se_{t-1} \qquad (3)$$

where O_t is the amount of water release in the present month, MCM/month, r_i is release-effective storage ratio, month^{-1}, Se_{t-1} is the antecedent storage.

5) Apply the general and flood dam operation model by integrating the release rules, the water demand decision making module, the water demand decision making module and the water network balance module.

6) Assess the impact of climate change on the reservoir water balance, water shortage, spillage and accumulative runoff at the downstream by general and flood control dam operation.

D.2 Adaptive reservoir operation model

The adaptive reservoir operation model includes 5 components follow as:1) input state variables; 2) reservoir water balance module; 3) modified ANFIS release decision making module; 4) water demand decision making module (see detail in Appendix D.1.6) ; 5) water network balance process (see detail in Appendix F). The detail of adaptive reservoir operation model follow as:

D.2.1 Adaptive Neuro Fuzzy Logic (ANFIS) concept

The reservoir operation in this study was developed by the Adaptive neuro fuzzy logic (ANFIS) rule base. The mainly idea of this ANFIS methodology included the concept of fuzzy logic, Fuzzy Inference Systems (FIS) and Adaptive Neuro-Fuzzy Inference Systems (ANFIS).

D.2.1.1 The concept of fuzzy logic

This topic explained the concept and definition of the words that related with this study. There are many necessary fuzzy logic knowledge and some keywords included:

1) Fuzzy set theory

Fuzzy logic is the supporting tool for making the decision under the uncertainty and ambiguously data. The fuzzy logic also provides for unclear objective and allows to have the flexibility by imitating the complex of the human thinking. Hence, the characteristic of fuzzy logic is more specific than the Boolean logic. The conceptual of fuzzy logic expands the partial true or grays part, that the real value will be in the range between the completely true and completely false. While the Boolean logic will be the value as “true” and “false” or “white” and “black” only.

Let X be a universe set of x values (elements). Then A is called a fuzzy (sub) set of X, if A is a set of ordered pairs:

$$A = \{(x, \mu_A(x)), x \in X, \mu_A(x) \in [0,1]\} \qquad (4)$$

where $\mu_A(x)$ is the grade of membership (or degree of belief) of x in A. The function $\mu_A(x)$ is called the membership function of A. A fuzzy set is called a fuzzy number if it is normal (i.e. the maximum of the memberships is 1) as well as convex.

2) Membership functions (MFs)

Membership functions are fuzzy sets that can be represented through mathematical expressions by taking into consideration the normality and convexity properties. In general, fuzzy sets can be of triangular, trapezoidal, Gaussian, or other form. In the transition regions, its MF parts can be linear, quadratic, or exponential, depending on the object of interest. The membership function embodies the mathematical representation of membership in a set, and the notation of a fuzzy set of A, where the functional mapping is given by

$$\mu_A(x) \in [0,1] \tag{5}$$

And the symbol $\mu_A\ (x)$ is the degree of membership of element x in fuzzy set A. Therefore $\mu_A\ (x)$ is a value on the unit interval that measures the degree to which element x belongs to fuzzy set A; equivalently, $\mu_A\ (x)$ = degree to which x∈A.

The trapezoidal MF is a function of a support vector x and depends on four scalar parameters (a, b, c, and d), as shown in Figure D-9. The mathematical expression of this MF is given by:

$$(x) = \begin{cases} 0, x \leq a \\ \frac{x-a}{b-a}, a \leq x \leq b \\ 1, b \leq x \leq c \\ \frac{d-x}{d-c}, c \leq x \leq d \\ 0, d \leq x \end{cases} \tag{6}$$

Or, more compactly, by:

$$\mu(x) = max\left[min\left(\frac{x-a}{b-a}, 1, \frac{d-x}{d-c}\right), 0\right] \tag{7}$$

The parameters a(b) and d(c) locate the left and right limits of the support. It is obvious that the triangular MF is a special case of the trapezoidal MF when b=c; and if a=b=c=d, then a fuzzy singletion is obtained. Furthermore, a,b,c,and d represent lower modal, left spread, upper modal, and right spread, respectively.

Traditional mathematics and logic assign a membership degree (MD) of 1 to items that are members of a set and 0 to those that are not. This is the dichotomy principle. Such a strong principle inevitably runs into philosophical problems. Fuzzy set theory offers a resolution to such problems. More importantly, it offers a logic that closely imitates the human thought process by allowing for approximate reasoning and vagueness. It allows a proposition to be neither “fully true” nor “fully false” but “partly true” and “partly false” to a given degree. It is common to restrict these MDs to the real inclusive interval [0,1].

The fuzzy set can be thought of as the transformer of different discourses within each set into a map, which assumes values within the positive unit interval. For instance, if the rainfall intensity, I, is the name of the whole set and “small” rainfall intensity is one of the subsets, then as the smallness of intensity deviates from this peak value of 1, the fuzzy set starts to decrease in a monotonous manner, down to 0 on both sides. (Figure D.9)

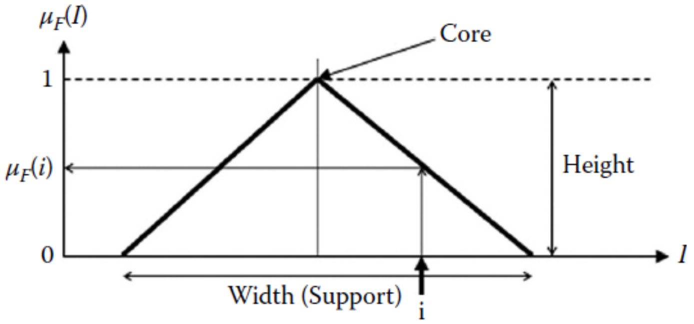


Figure D.9 Fuzzy set with triangular MF

3) Linguistic variables

Fuzzy logic has the ability to express the amount of ambiguity in human thinking and subjectivity, including natural language, and hence words, adjectives, and sentences in a comparatively undistorted manner. Linguistic variables are the most fundamental elements in human knowledge exposition and dissemination.

4) Knowledge base

The knowledge base is specified to the application domain with facts about the domain and rules that describe relations in the domain. Herein, “IF . . . , . . . , . . . THEN . . . , . . . ,” rules are by far the most popular formalism for presenting knowledge.

5) Fuzzy rule base

Fuzzy rule base is to transform the human knowledge to the logic in the form of Linguistic variables by combining the basic structure that is IF Premise (antecedent), THEN Conclusion (consequent). A set of rules represents the internal associations between input variables, and then such combinations are related to output fuzzy sets through logical proportional, indirectly proportional, or other type of relationship. The representative (valid) set of rules is obtained for the hydrologic phenomenon under consideration. The fuzzy rule base includes all the features of mathematical formulation of an event but in terms of words and propositions in the form of “IF . . . THEN . . .” statements such as IF Storage high and Inflow normal THEN Release slightly more etc.

D.2.1.2 Fuzzy Inference Systems (FIS)

D.2.1.2.1 Fuzzy inference system mechanism

Fuzzy Inference Systems (FIS) is the actual process of mapping from a given set of input variables to an output based on a set of fuzzy rules, which are the essence of the modeling. The general framework of the FIS structure is presented in Figure D-10. The general fuzzy inference engine proceeds in four steps: (Sen, 2010)

1) Fuzzification: The MFs defined in the input variables are applied to their actual values to determine the membership degree (MD) for each rule premise. In the fuzzification stage, the following points are important:

1.1) In hydrological modeling, there is a single output variable, whereas there may be many input variables. In general, it is multiple-input-single-output (MISO) modeling.

1.2) The variability range of each linguistic variable must be determined linguistically as closed-interval, left-open-interval, right-open-interval, or open interval from both sides. For instance, the “porosity” linguistic variable has closed-interval because it is confined between 0 and 1, inclusive; “rainfall” has right-open interval; “water deficit” should have left-open interval; and “temperature” has open-interval,

1.3) The number of fuzzy sets for linguistic variable fuzzification into several categories must be determined.

1.4) The shapes of fuzzy sets in the form of MFs must be determined and it is advised here to depend on triangular and trapezium MFs initially for model establishment.

1.5) In any fuzzification procedure of any linguistic variable, the most right and left side MFs must reach to MDs equal to 1; and if the linguistic variable has open-interval, then end MFs must take the form of trapezium.

2) Inference: The MD for the premise of each rule is computed and applied to the conclusion part of each rule. This results in one fuzzy subset to be assigned to each output variable for each rule. According to either “minimum”, “ANDing,” or “product” conjunctives, the output MF is clipped off at a height corresponding to the rule premise’s computed MD. In the “product” inference, the rule premise’s computed MD scales the output MF.

3) Composition: All the fuzzy subsets assigned to each output variable are combined together to form a single fuzzy subset for each output variable. Again, usually “maximum” or “summation” is used. In “maximum” composition, the combined output fuzzy subset is constructed by taking the pointwise maximum over all the fuzzy subsets assigned to a variable by the inference rule, which corresponds to FL “ORing.” In “summation” composition, the combined output fuzzy subset is constructed by taking the pointwise sum over all the fuzzy subsets assigned to the output variable by the inference rule.

4) Defuzzification: The defuzzification is the reverse process of fuzzification. It converts the confidences in a fuzzy set of word descriptors into a real number. There are many defuzzification available for fuzzy control such as arithmetic average, weighted average, center of gravity, smallest of maxima, largest of maxima, mean of the range of maxima and local mean of maxima.

There are Fuzzy Inference Systems (FIS) model that used in the fuzzy inference engine such Mamdani (1974) FIS, Sugeno FIS, Tsukumoto FiS and Sen FIS. Thus, this study applied Sugeno FIS according to the Adaptive Neuro-Fuzzy Inference Systems (ANFIS).

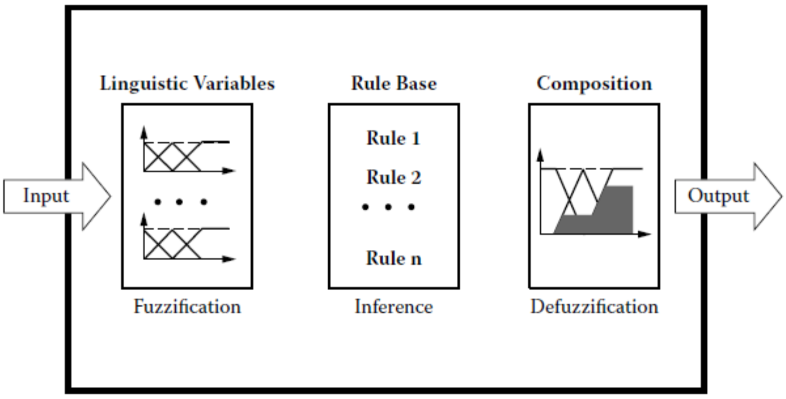


Figure D.10 General FIS structure

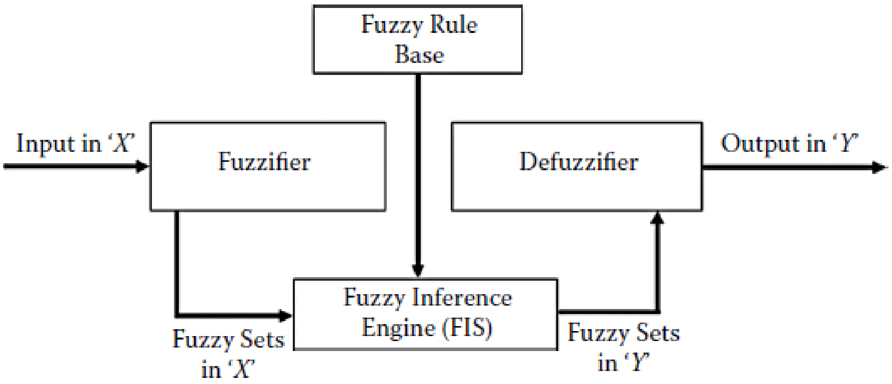


Figure D.11 General fuzzy system

D.2.1.2.2 Sugeno FIS

This model is also known as Takagi-Sugeno-Kang (TSK) FIS according to its proposers' initials (Sugeno, 1985; Takagi and Sugeno, 1985. They devised a systematic approach for generating fuzzy rules from a given set of input-output data. The rule base generated by considering only the antecedent parts of the rules remains the same but the difference comes in attaching consequent parts, which are no longer in the form of fuzzy sets but simple linear mathematical functions. In a two-input ("X" and "Y") and single-output ("Z") domain, a typical rule takes the following form:

R: "IF X is 'small' AND Y is 'large' THEN Z = f (X, Y)"

where f(X, Y) is a crisp function that constitutes the consequent part of the fuzzy rule. Usually, it has a linear form in terms of input variables X and Y. Its representative form can be obtained from a given set of data, or it can also be any function as long as it can appropriately describe the output of the model within the fuzzy region specified by the antecedent part of the rule base. In practical works, two alternatives of f(X, Y) are used. One alternative has a constant (c) consequent part as

R: "IF X is 'small' AND Y is 'large' THEN Z = c"

which is also referred to as a zero-order TSK or Sugeno FIS. The other alternative has a linear consequent part known as a first-order Sugeno FIS:

R: "IF X is 'small' AND Y is 'large' THEN Z = c + aX + bY."

If there are more than two variables, then the consequent part of each rule base appears similar to a linear multiple regression expression. This alternative is similar to a linear interpolation procedure, the only difference being that the interpolated point has some MD depending on the aggregation of the input variables through the fuzzy word MFs in the antecedent part of the rules. The zero-order Sugeno FIS yields a smooth function of its input variables as long as the neighboring MFs have enough overlap. Even in the Mamdani FIS, the smoothness of the output can be obtained through the overlapping of MFs in the antecedent part, whereas the consequent part does not play any role in such a smoothing procedure. It is therefore possible to adjust the smoothness of the final functional form by playing with the antecedent part MFs either through "trial and error" or by a "systematic" approach such as adaptive-network-based FIS (ANFIS), which includes neural networks or genetic algorithms (Sen, 2004a, b). On the other hand, the Sugeno FIS structure can be presented as in Figure D-12 where the output appears in the form of a weighted average as:

$$\hat{Z} = \frac{\sum_{i=1}^{n} w_i f_i}{\sum_{i=1}^{n} w_i} = \sum_{i=1}^{n} a_i f_i \qquad (8)$$

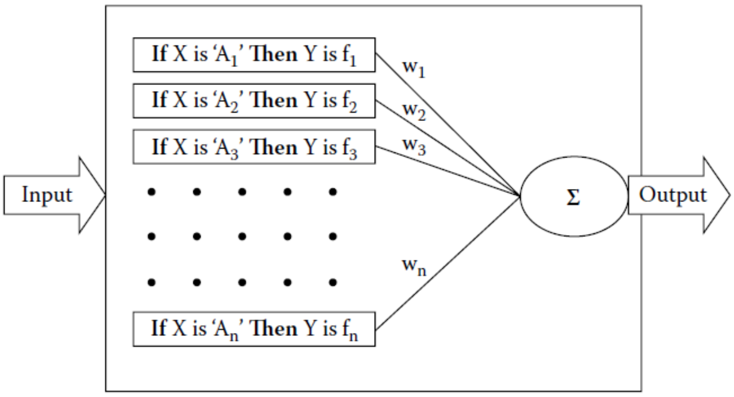


Figure D.12 Sugeno FIS structure

D.2.1.2 Adaptive Neuro-Fuzzy Inference Systems (ANFIS)

D.2.1.2.1 ANFIS Architecture

The adaptive-network-based FIS (ANFIS) model was proposed by Jang (1992) and applied successfully to many problems. ANFIS identifies a set of parameters through a hybrid learning rule that combines back-propagation gradient descent and a least squares method. It can be used as a basis for constructing a set of fuzzy "IF . . . THEN . . . " rules with appropriate MFs to generate the preliminary stipulated input-output pairs.

ANFIS applications and properties were investigated and several methods were proposed for partitioning the input space and hence address the structure identification problem. Fundamentally, ANFIS is a graphical network representation of Sugeno-type fuzzy systems, endowed with neural learning capabilities. The network is comprised of nodes with specific functions and waves, and are collected in layers with specific functions.

To illustrate ANFIS's representational strength, the neural fuzzy control system is considered based on the Sugeno fuzzy rules whose consequent parts are linear combinations of their preconditions. The Sugeno fuzzy rules are in the following forms:

$$R^j: IF\ x_i\ is\ A_1^j\ AND\ x_2\ is\ A_2^j\ AND\ \dots\dots..AND\ x_n\ is\ A_n^j$$

$$THEN\ f_j = a_0^j + a_1^j x_1 + a_2^j x_2 + \cdots + a_n^j x_n$$

where $x_i's$ (i = 1, 2, . . . , n) are input variables, y is the output variable, A_i^j are linguistic words of the antecedent part with MFs

$\mu_{A_i^j}(x_i)$, , (j = 1, 2, . . . , n), and $A_1^j \in R$ are coefficients of linear equations $f_i(x_1, x_2, ... x_n)$.

Assume that the fuzzy control system under consideration has two inputs x_1 and x_2, one output, and that the rule base contains two Sugeno fuzzy rules as follows (Figure D.13a):

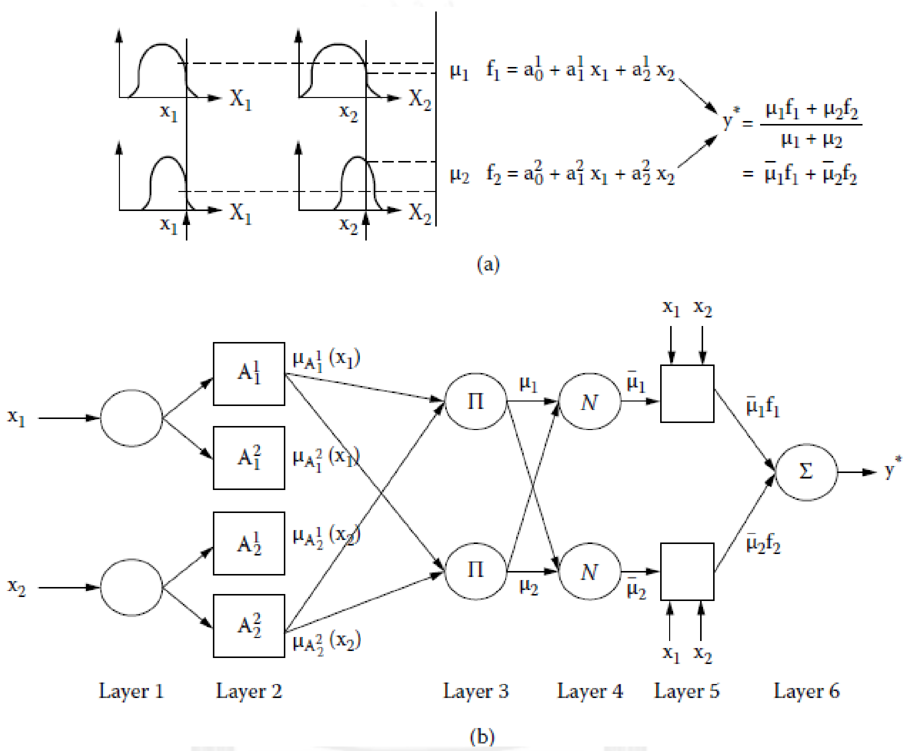


Figure D.13 Structure of ANFIS: (a) FIS and (b) ANFIS (Sen, 2010 : p.222)

The fuzzification is inferred through weighted averaging in Eq. (8), where wj's are the firing strengths of Rj, (j = 1, 2) and are given by:

$$\omega_j = \mu_{A_1^j}(x_1) + \mu_{A_2^j}(x_2) \ , \ \text{j=1, 2.} \qquad (8)$$

If "product" inference is used, then the corresponding ANFIS architecture is shown in Figure D-13, where functions in the same layers are of the type described below. This is an artificial neural network architecture where the following meanings can be attached to each layer:

1) Layer 1: Every node in this layer is an input node that just passes external signals to the next layer.

2) Layer 2: Every node in this layer acts as an MF, $\mu_{A_i^j}(x_i)$, and its output specifies the degree to which the given x_i satisfies the quantifier A_i^j.

Generally, $\mu_{A_i^j}(x_i)$ is selected as bell-shaped with a maximum equal to 1 and minimum equal to 0, such as (Figure D-9):

$$\mu_{A_i^j}(x_i) = \frac{1}{1+\left\{\left[(x_i - m_i^j)/\sigma_i^j\right]^2\right\}b_i^j} \tag{9}$$

or

$$\mu_{A_i^j}(x_i) = exp\left\{-\left[\left(\frac{x_i-\mu_i^j}{\sigma^j}\right)^2\right]^{b_i^j}\right\} \tag{10}$$

Where $[m_1^j,\ \sigma_1^j\ , b_i^j]$ is the parameter set to be tuned. In fact, continuous and piecewise differentiable functions, such as commonly used triangular or trapezoidal MFs, are also qualified candidates for node functions in this layer. Parameters in this layer are referred to as precondition parameters.

3) Layer 3: Every node in this layer is labeled $\mathbf{\Pi}$, and multiplies the incoming signals $\mu_j = \mu_{A_1^j}(x_1) + \mu_{A_2^j}(x_2)$ and sends out the product. Each node output represents the firing strength of a rule.

4) Layer 4: Every node in this layer is labeled N and calculates the normalized firing strength of a rule. That is, the j-th node calculates the ratio of the *j*-th rule's firing strength of all the rules' firing strengths as:

$$\overline{\omega}_j = \mu_j/(\mu_{A_1^j}(x_1) + (\mu_{A_2^j}(x_2)) \tag{11}$$

5) Layer 5: Every node *j* in this layer calculates the weighted consequent value as:

$$\overline{\omega}_j(a_0^j + a_1^j x_1 + a_2^j x_2) \tag{12}$$

where $\overline{\omega}_j$ j is the output of layer 4 and $\{a_0^j, a_1^j x_1, a_2^j x_2\}$ is the set to be tuned. Parameters in this layer are referred to as consequent parameters.

6) Layer 6: The only node in this layer is labeled Σ, and it sums all incoming signals to obtain the final inferred result for the whole system (Lin and Lee, 1996).

D.2.1.2.2 Hybrid learning algorithm

From the ANFIS architecture shown in Figure D-13 (b), we observe that when the values of the premise parameters are fixed, the overall output can be expressed as a linear combination of the consequent parameters. In symbols, the output *f* in Figure D.13 (b) can be rewritten as

$$f = \frac{w_1}{w_1+w_2} f_1 + \frac{w_2}{w_1+w_2} f_2 \tag{13}$$

$$= \overline{w}_1(p_1 x + q_1 y + r_1) + \overline{w}_2(p_2 x + q_2 y + r_2) \tag{14}$$

$$= \overline{w}_1 x)p_1 + (\overline{w}_1 y)q_1 + (\overline{w}_1)r_1 + (\overline{w}_2 x)p_2 + (\overline{w}_2 y)q_2 + (\overline{w}_2)r_2 \tag{15}$$

Which is linear in the consequent parameters p_1, q_1, r_1, p_2, q_2, and r_2. From this observation, we have

S= set of total parameters,

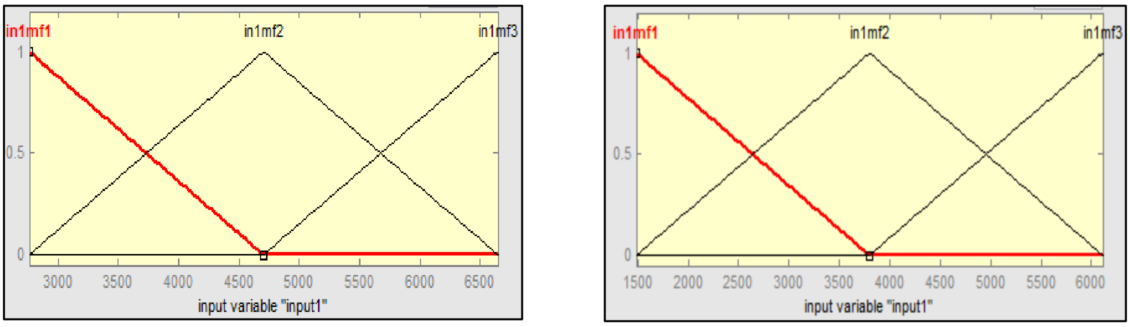
S_1=set of premise(nonlinear) parameters,

S_2=set of consequent (linear) parameters

D.2.2 State variable of the decision process

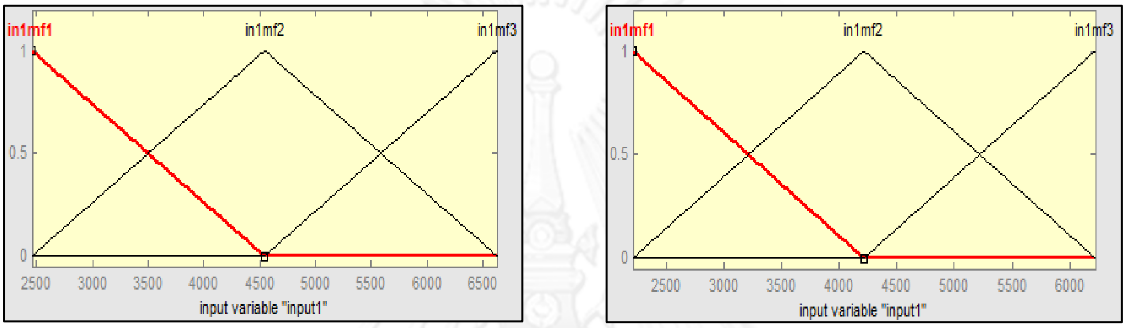
The state variables of the decision of release are the antecedent effective storage, inflow, side flow of the middle Nan River Basin, rainfall at the downstream and irrigation water demand. The output variable is the release of Sirikit Dam. The propose of release decision will be responding to reduce water deficit and spillage of dam. While these variables depend on the uncertainty condition and error recorded data that is difficult to identify the exactly values. From this reason, the membership function (MF) will be represented the uncertainty variables. The characteristics of membership functions follow as:

1) Membership function of the antecedent effective storage show as Figure D.14.
2) Membership function of the inflow show as Figure D.15.
3) Membership function of the side flow of middle Nan River Basin show as Figure D.16.
4) Membership function of the rainfall at the lower Nan River Basin show as Figure D.17.
5) Membership function of the irrigation water demand show as Figure D.18.



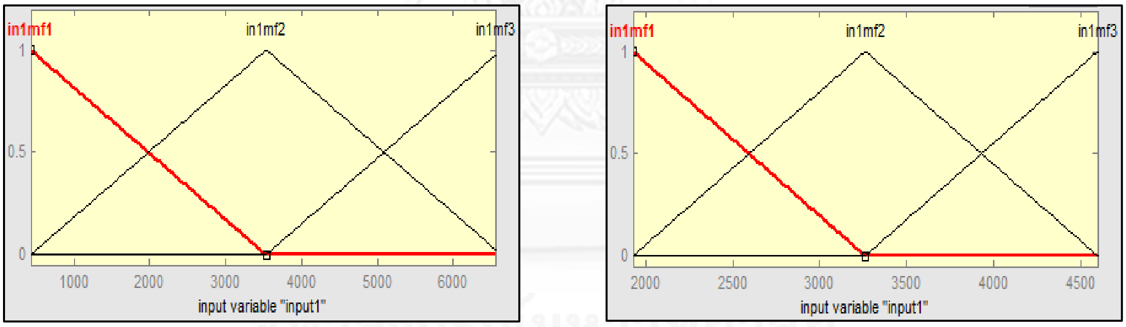
(a) High_wet

(b) High_dry



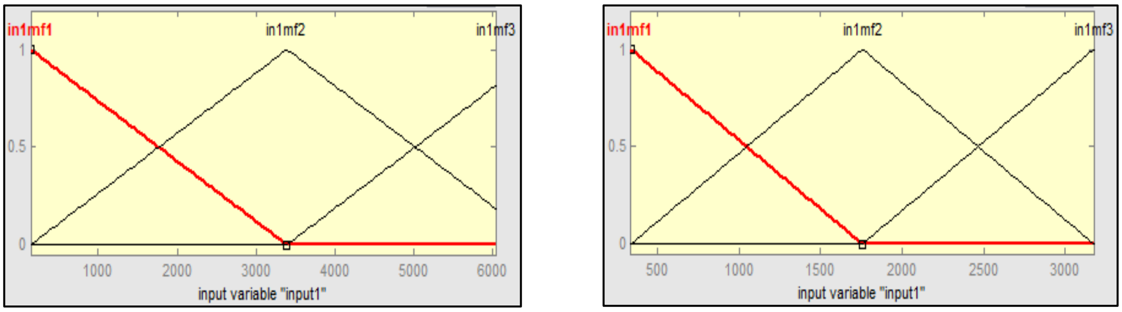
(c) Normal_wet

(d) Normal _dry



(e) Dry_wet

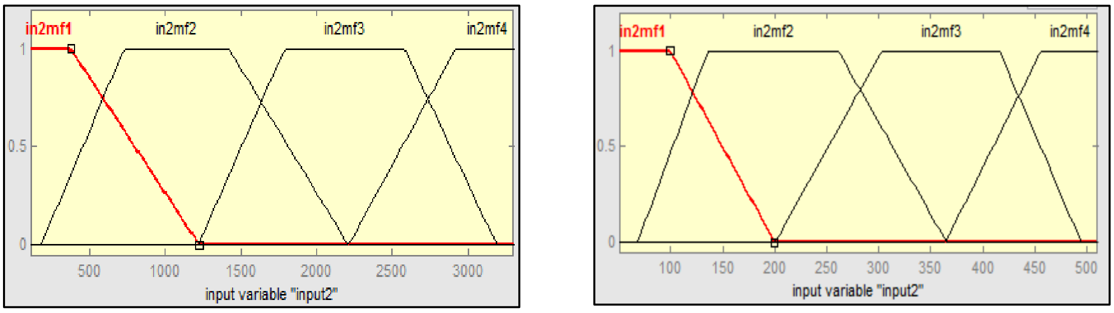
(f) Dry_dry



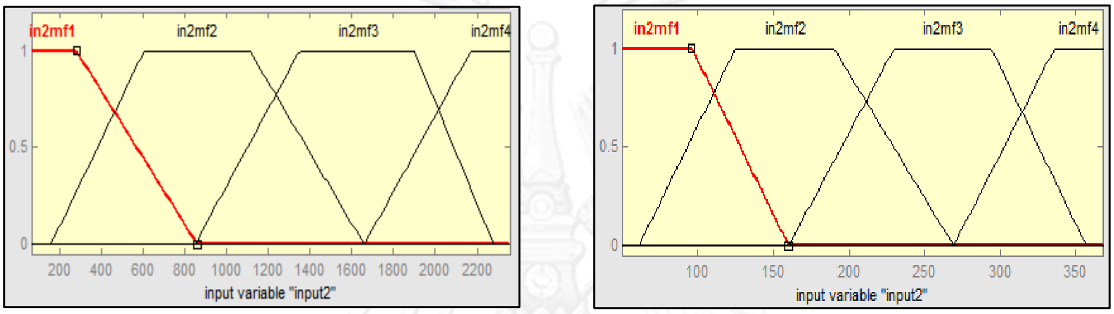
(g) Very Dry_wet

(h) Very Dry_dry

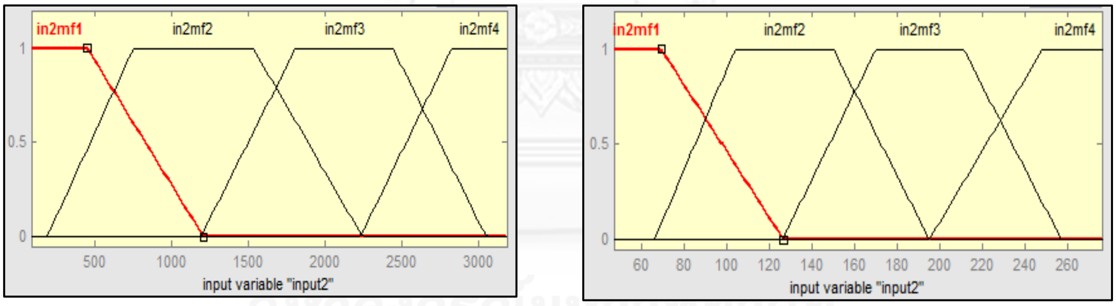
Figure D.14 Membership function of the antecedent effective storage



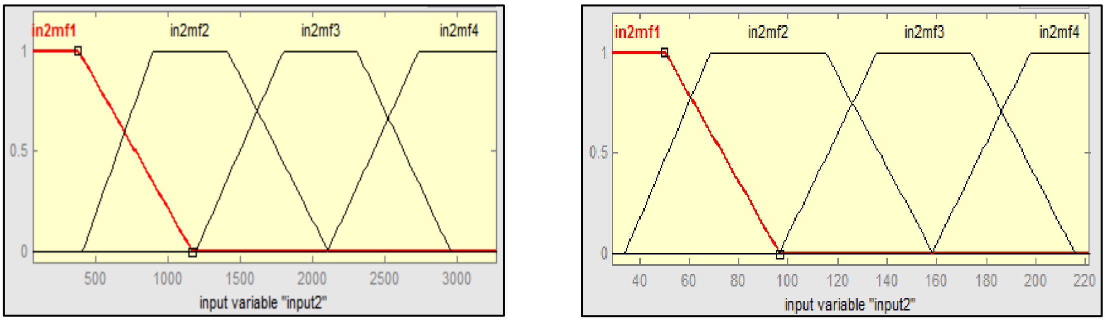
(a) High_wet (b) High_dry



(c) Normal_wet (d) Normal _dry

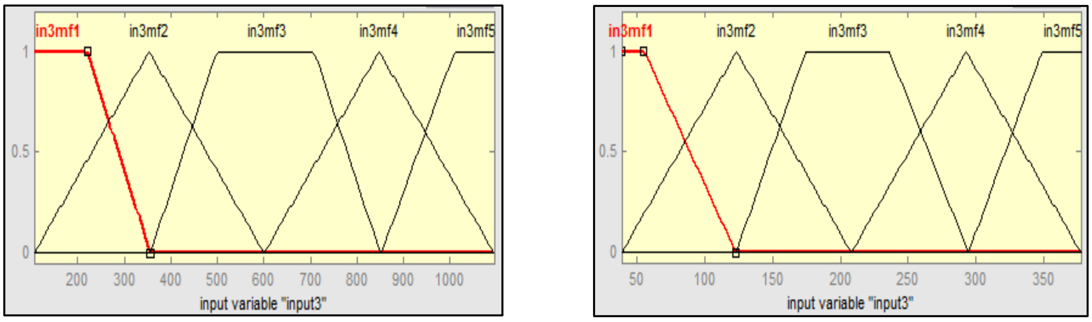


(e) Dry_wet (f) Dry_dry



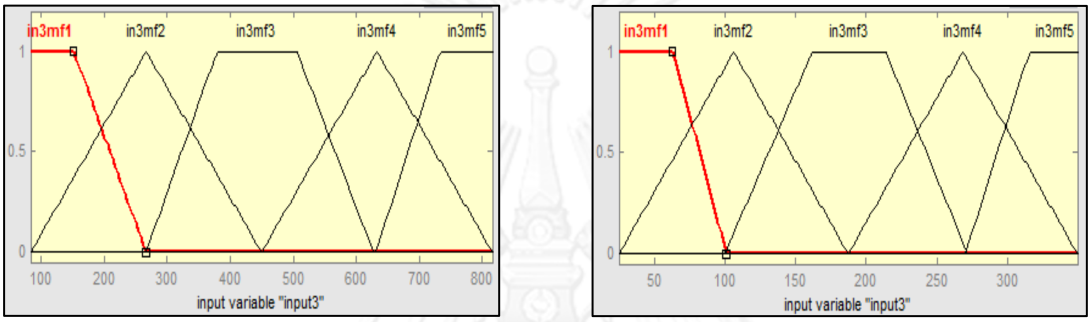
(g) Very Dry_wet (h) Very Dry_dry

Figure D.15 Membership function of the inflow



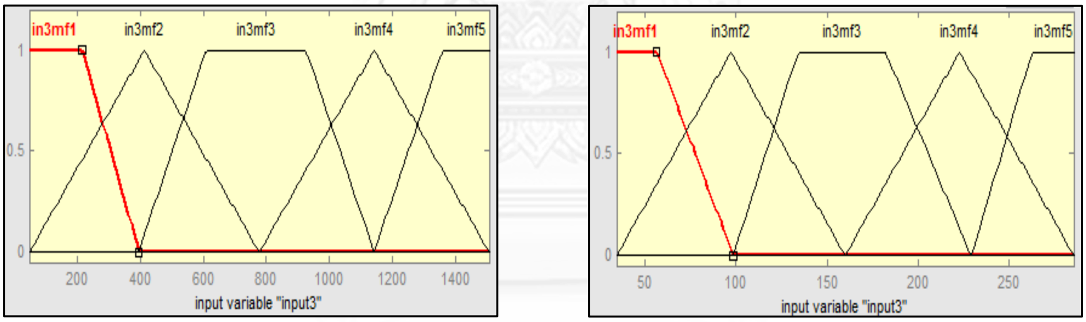
(a) High_wet

(b) High_dry



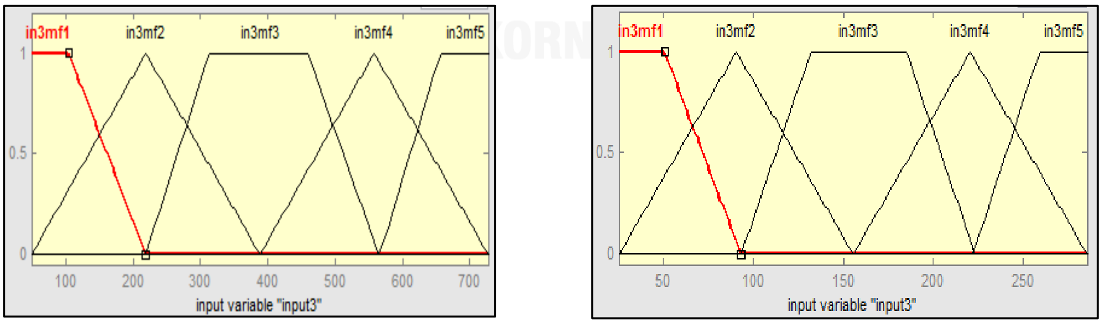
(c) Normal_wet

(d) Normal _dry



(e) Dry_wet

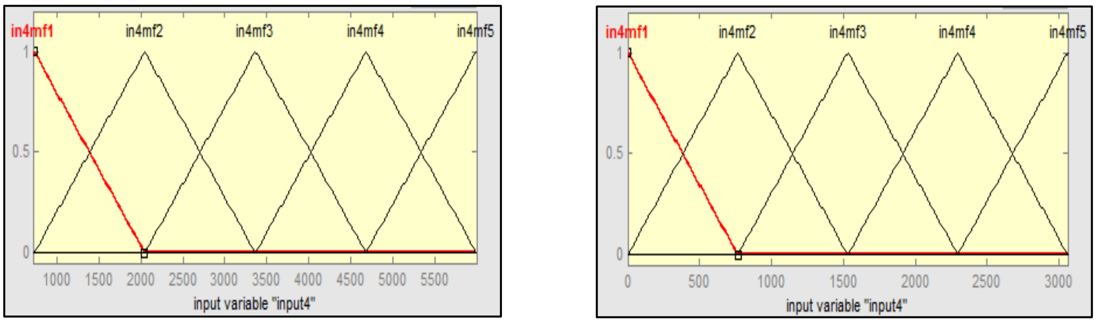
(f) Dry_dry



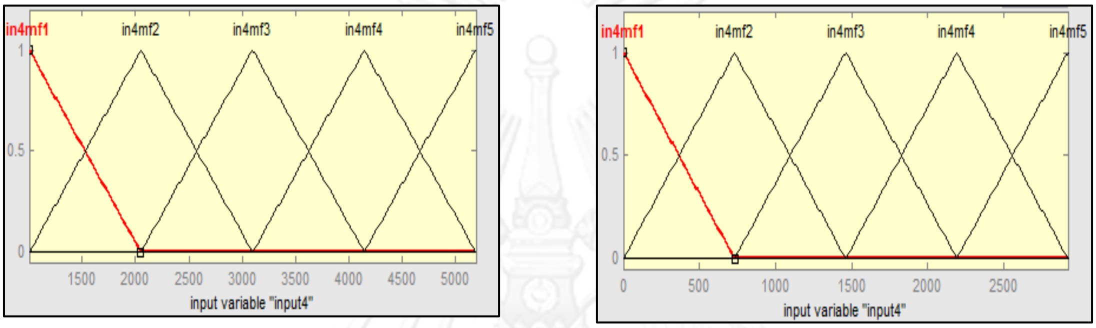
(g) Very Dry_wet

(h) Very Dry_dry

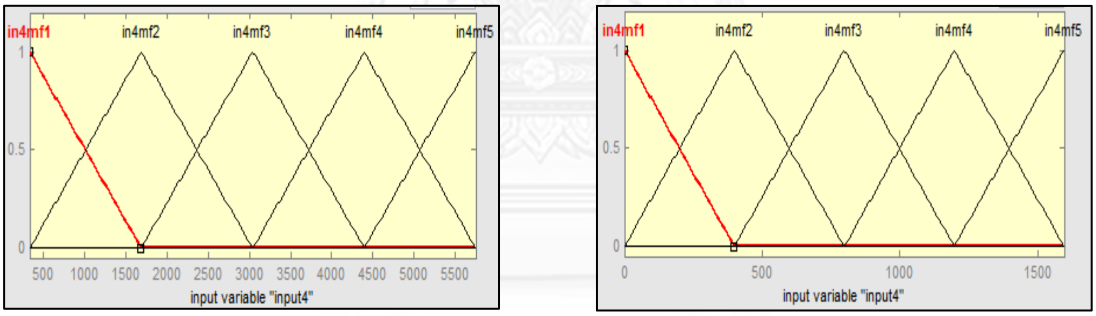
Figure D.16 Membership function of the side flow of middle Nan River Basin



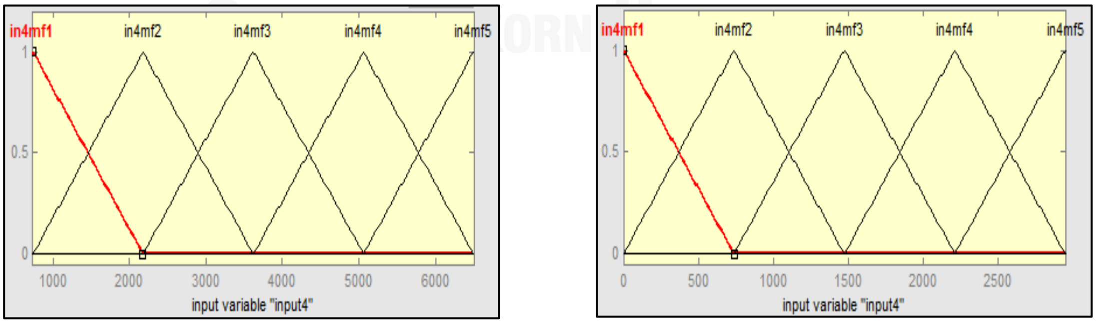
(a) High_wet (b) High_dry



(c) Normal_wet (d) Normal _dry

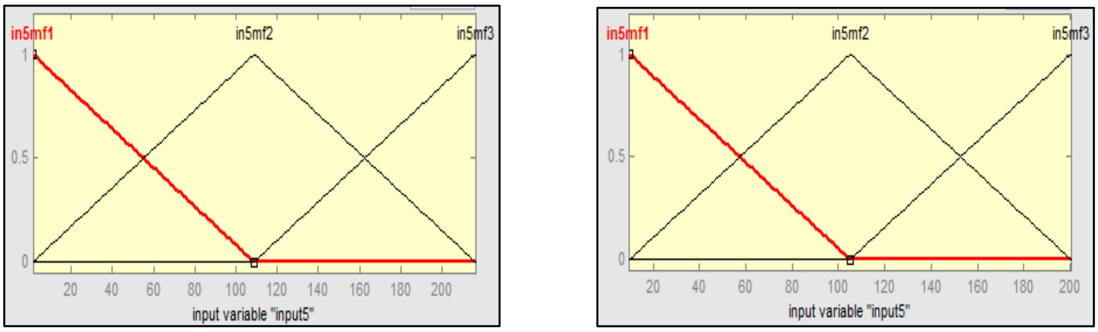


(e) Dry_wet (f) Dry_dry

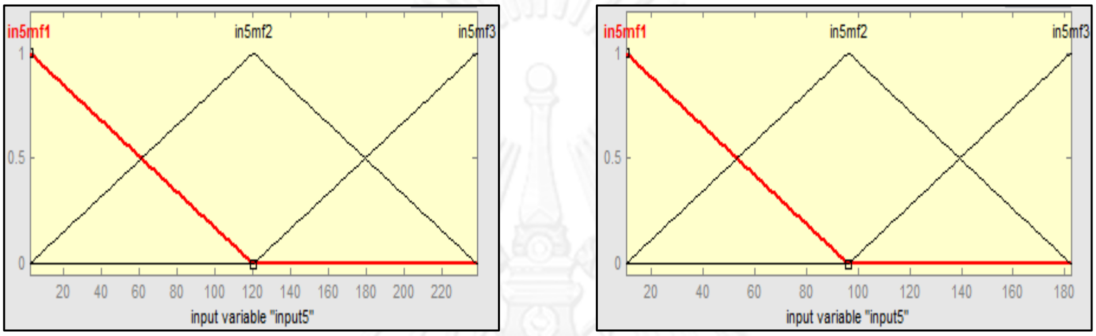


(g) Very Dry_wet (h) Very Dry_dry

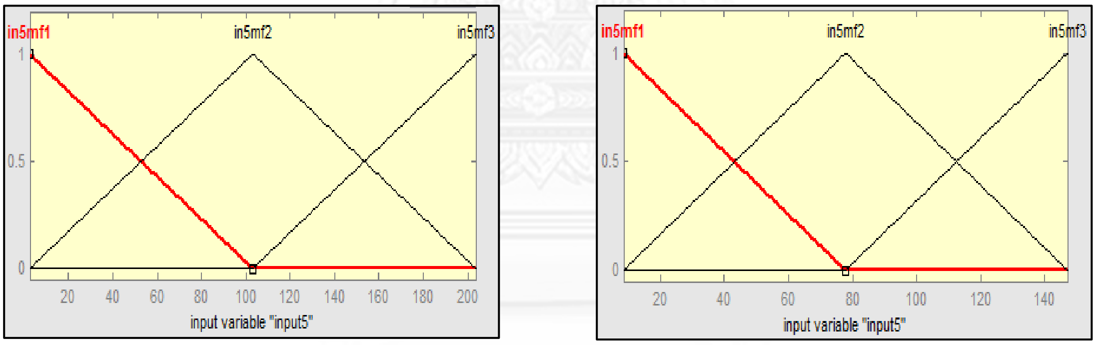
Figure D.17 Membership function of the rainfall at the lower Nan River Basin



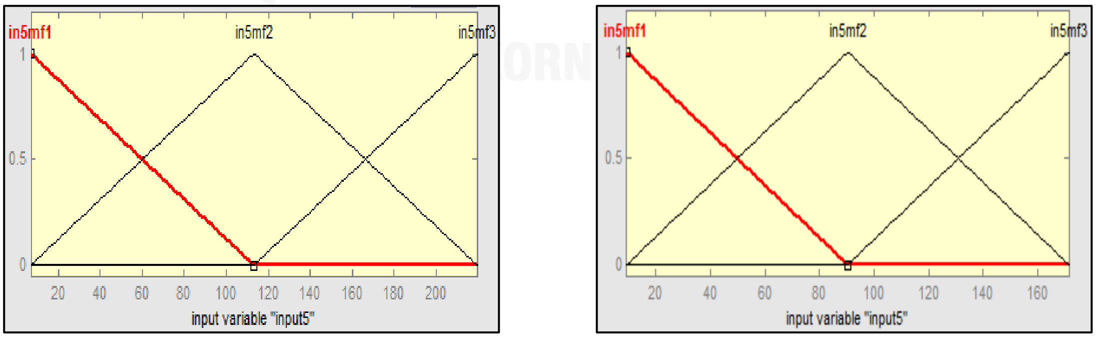
(a) High_wet (b) High_dry



(c) Normal_wet (d) Normal _dry



(e) Dry_wet (f) Dry_dry



(g) Very Dry_wet (h) Very Dry_dry

Figure D.18 Membership function of the irrigation water demand

D.2.3 Adaptive neuro fuzzy inference system (ANFIS) dam operation system component

The ANFIS dam operation system composes the dynamic system simulation and adaptive neuro fuzzy inference system to decide releasing water from reservoir under the uncertainty condition. This model includes 5 parts follow as:

1) Input variables include the initial storage (Sti), the inflow (It), sideflow (SF), rainfall at downstream basin (Rt) and water demand (Wdt) (see detail in D.2.2)

2)Reservoir water balance model which adopts the water storage concept. This process will receive the input variables and water release decision making module.

3)ANFIS water release decision making model includes the fuzzification, the inference and the defuzzification. The fuzzification uses the membership function to represent the uncertainty of input variables by applying rule base (IF-THEN). The inference is the decision making logic to decide release from reservoir. While the defuzzification is to transform the uncertainty amount to the values, and then send the values to part 2).

4)Water demand decision making process which uses the tree probability classification to determine the crop cultivation area depends on the storage state at the end of season. The output will be sent to part 2). The detail of water demand decision making module shows in D.1.6.

5)Water network balance model which calculates the water deficit by receiving the release values from part 3) and the water demand from part 4), respectively. The detail of water network balance model shows in Appendix F.

This model is calibrated by selecting the shape of membership function and a number of membership function (MF) for specific model architecture. Five input variables and output variables are considered in ANFIS toolbox.

D.2.4 ANFIS dam operation rule generation processes

1) Collect the reservoir operation data of Sirikit Dam in year 1979 – 2012 e.g. inflow, release and storage.

2) Estimate the existing water demand from the historical cultivated area, water consumption of plant coefficient, crop pattern and some meteorological data for calculating the evapotranspiration such as maximum and minimum temperature and relative humidity etc. Thus, the water demand which is the state variable would be focused on the Phitsanulok Irrigation Project.

3) Create the probability of antecedent effective storage and determine the water season, and then set up the water season in wet and dry season. The water seasons were defined according to the seasonality of weather in Thailand such as the rainy season or south-west monsoon season (May to October) as wet water season and dry season or north-east monsoon season (November to April) as dry water season. On the other hand, the water season also depends on the cultivation season of the farmers in Thailand.

4) Classify the state variables for training the ANFIS release functions included input and output variables by using probability decision tree method, and then classified to be high, normal, dry and very dry water season. The wet season start from Apr 30 and dry season start from Oct 31. The input and output variables follow as:

Input variables : antecedent effective storage, inflow, rainfall at downstream basin and water demand

Output variable : release

However the state variables were classified into the water season and seasonality of weather, the classification of state variables can be incorporated to 8 ANFIS rules such as:

- High water season in wet season
- High water season in dry season
- Normal water season in wet season
- Normal water season in dry season
- Dry water season in wet season
- Dry water season in dry season
- Very dry water season in wet season
- Very dry water season in dry season

5) Prepare the state variables files and load data into the ANFIS toolbox in the MATLAB program.

6) Generate ANFIS according to the ANFIS theory by using ANFIS toolbox in the MATLAB program follows as:

6.1) Generate FIS by following the steps as:

- Select the grid partition as the generating FIS method.
- For the input variables, assign the number of membership function (MFs) to each input variable, and then select the trapezoidal MF type.
- For the output variable, select the linear MF type.

6.2) Select the hybrid optimization method.

6.3) FIS properties :

- For And method, select “prod”.
- For Or method, select “probor”.
- For the defuzzification, select the weighted average method.
- For FIS type, select “Sugeno FIS”.

6.4) For the fuzzy rule base, select connection as “and”.

7) Evaluate the ANFIS release functions by incorporating this ANFIS release functions into reservoir operation model, and then verify the release results by the goodness of fit test indices such as the correlation (R2), the root mean square error (RMSE) and the standard error. The ANFIS release functions will call as the existing reservoir operation rule.

The trial-and-error approaches are used to identify the optimal model structure. Three shapes of membership function and the 18 number of membership function (MF) was compared to select the suitable shapes of membership function show as Table D-6. The calibration results are shown in Table D-7.

Table D.6 The goodness of fit test of membership shape selection

Numbers of MF	Triangle			Trapizoidal			Gbell		
	R^2	RMSE	SE	R^2	RMSE	SE	R^2	RMSE	SE
3,3,3,3,3	0.24	354	256	0.01	480	292	0.39	324	230
3,4,3,3,3	0.45	260	217	0.21	381	261	0.25	345	253
3,5,3,3,3	0.01	507	292	0.01	507	292	0.01	489	292
4,3,3,3,3	0.24	342	256	0.16	399	269	0.01	488	292
4,4,3,3,3	0.46	259	215	0.002	495	293	0.01	488	291
4,5,3,3,3	0.23	372	257	0.29	345	246	0.01	503	291
5,3,3,3,3	0.18	381	266	0.02	509	291	0.02	522	290
5,4,3,3,3	0.44	273	220	0.01	503	291	0.001	491	293
4,3,4,3,3	0.02	436	291	0.02	423	282	0.18	369	266
4,3,5,3,3	0.001	465	293	0.001	474	284	0.004	482	293
4,4,4,3,3	0.21	335	260	0.18	367	265	0.37	300	232
4,4,5,3,3	0.31	296	243	0.11	404	257	0.35	305	237
3,4,5,3,3	**0.48**	**256**	212	0.16	381	268	0.007	478	292
3,4,4,3,3	0.42	265	223	0	483	293	0.004	476	293
4,5,4,3,3	0.36	311	234	0.03	442	289	0.001	500	293
3,3,4,3,3	0.37	293	233	0.0003	470	293	0.007	484	292
3,3,5,3,3	0.35	294	237	0.25	365	254	0.29	347	247
5,4,4,3,3	0.34	306	238	0.02	510	290	0.31	328	243

Table D.7 The goodness of fit test of membership function for model calibration

Numbers of MF	R^2	RMSE	SE	Numbers of MF	R^2	RMSE	SE
3,3,3,3,3	0.24	354	256	3,4,4,4,5	0.24	313	248
3,3,3,3,4	0.01	476	283	3,4,4,5,3	0.49	249	209
3,3,3,3,5	0.003	465	284	3,4,4,5,4	0.31	312	226
3,3,3,4,3	0.18	370	266	3,4,5,3,3	0.16	381	268
3,3,3,4,4	0.33	328	240	3,4,5,3,4	0.23	306	241
3,3,3,4,5	0.0005	449	284	3,4,5,3,5	0.17	370	268
3,3,3,5,3	0.01	423	283	3,4,5,4,3	0.31	297	243
3,3,3,5,4	0.002	464	284	3,4,5,4,4	0.3	294	228
3,3,3,5,5	0.21	358	252	3,4,5,5,4	0.71	105	103
3,3,4,3,3	0.37	293	233	**3,4.5,5,3**	**0.89**	**80**	**79.6**
3,3,4,3,4	0.0002	441	272	3,5,3,3,4	0.01	486	292
3,3,4,3,5	0.004	443	272	3,5,3,3,5	0.17	369	266
3,3,4,4,3	0.28	330	249	3,5,3,4,3	0.56	165	155
3,3,4,4,4	0.34	314	239	3,5,3,5,3	0.42	271	223
3,3,4,4,5	0.29	336	246	3,5,4,3,3	0.0003	461	293
3,3,4,5,3	0.36	289	234	3,5,4,3,4	0.0008	466	293
3,3,4,5,4	0.0003	449	283	3,5,4,4,3	0.39	286	229
3,3,4,5,5	0.0002	455	283	3,5,5,3,3	0.48	261	211
3,3,5,3,3	0.35	294	237	4,3,3,3,4	0.01	496	292
3,3,5,3,4	0.24	348	255	4,3,3,3,5	0.2	370	262
3,3,5,3,5	0.16	362	250	4,3,3,4,3	0.28	338	250
3,3,5,4,3	0.29	312	230	4,3,3,4,4	0.29	338	247
3,3,5,4,4	0.26	331	233	4,3,3,5,3	0.26	341	253
3,3,5,4,5	0.1	410	278	4,3,3,5,4	0.01	490	292
3,3,5,5,3	0.28	320	248	4,3,4,3,3	0.35	323	236
3,3,5,5,4	0.23	353	257	4,3,4,3,4	0	482	293
3,4,3,3,3	0.21	381	261	4,3,4,3,5	0.26	329	252
3,4,3,3,4	0.4	279	227	4,3,4,4,3	0.31	323	244
3,4,3,3,5	0.01	480	291	4,3,4,5,3	0.35	308	237
3,4,3,4,3	0.45	267	217	4,3,5,3,4	0.001	467	293
3,4,3,4,4	0.38	287	214	4,3,5,3,5	0.09	400	280
3,4,3,4,5	0.36	301	235	4,4,3,3,4	0.01	488	292
3,4,3,5,3	0	428	272	4,4,3,3,5	0.003	479	293
3,4,3,5,4	0.35	291	219	4,4,3,4,3	0.45	269	218
3,4,4,3,4	0.36	302	235	4,4,3,4,4	0.00001	457	293
3,4,4,3,5	0.27	304	244	4,4,3,5,3	0.44	268	219
3,4,4,4,3	0.46	258	216	4,5,3,3,4	0.01	487	292
3,4,4,4,4	0.25	335	255	4,5,3,4,3	0.29	339	247

D.2.5 Modified ANFIS dam operation development

The objective of this adaptive reservoir operation development is to reduce the water deficit and spillage. In the modified ANFIS* reservoir operation development composes 2 processes such as 1) modify the general dam operation and 2) modify the ANFIS dam operation. The modified general dam operation is to improve the release rules to minimize the water deficit and spillage. Consequently, the modified ANFIS* dam operation will be used the output of adjusting general dam operation as input variable for improving the efficiency of ANFIS* dam operation. The modified ANFIS reservoir operation will be call as "ANFIS*". Thus, the release – antecedent effective storage ratio of general dam operation will be optimized for the appropriate release. The adjusted release – antecedent effective storage ratio of Sirikit Dam and Bhumibol Dam show as Table D-8 and D-9. The suitable increasing percentage was considered at the minimum water deficit, minimum spillage of reservoir, minimum number of shortage year and minimum continue shortage. However this study will focus to modify ANFIS release rules for Sirikit Dam only. Finally, the modified ANFIS dam operation model will be calibrated by selecting a number of membership function (MF).

1) Modify the general dam operation rule by adjusting the release – antecedent effective storage ratio to minimize the water deficit and spillage.

1.1) Increase the percentage of release-storage ratio in both wet and dry season to minimize amount of water deficit and number of water shortage years and compare the change in average monthly water deficit in each water season and monthly type.

1.2) Increase the percentage of release-storage ratio in dry season to minimize water spillage of reservoir and compare the change in average monthly water spillage in each water season and monthly level type.

1.3) The optimum point of release-storage ratio is found at the minimum water deficit and number of water shortage years for the water shortage events and on the other hand, the optimum point of release-storage ratio is found at the minimum water spillage.

2) Classify the results of adjusted general dam operation as the input and output variables based on the probability of the antecedent effective storage in wet and dry season.

3) Generate the ANFIS* water release decision making module.

4) Calibrate and verify the ANFIS* water release decision making module by adjusting the number of membership functions to increase the correlation and comparing with the actual dam operation. The correlation of the ANFIS* water release decision making rule show as Table D-10. (year 1987 – 1996 for model calibration and year 1997 – 2011 for model verification)

5) Validate is the final checking step before applying this model. The recorded data in year 1987 – 2011 will be used to compare the results with the actual dam operation.

6) Apply the reservoir operation model to assess the impact of climate change on the water deficit, the spillage and the flood conditions.

7) Evaluate the performance of adjusted ANFIS reservoir operation by comparing the results between the actual dam operation.

Table D.8 The adjusted release – antecedent effective storage ratio of Sirikit Dam

Rule	Water season	Monthly level	Releasing ratio (month^{-1})											
			May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
General	High	higher	0.21	0.24	0.08	0.17	0.21	0.11	0.06	0.06	0.08	0.13	0.17	0.20
		high	0.21	0.24	0.08	0.17	0.21	0.04	0.08	0.10	0.10	0.13	0.17	0.20
		medium	0.21	0.24	0.08	0.17	0.05	0.06	0.12	0.07	0.10	0.14	0.19	0.20
		low	0.15	0.15	0.16	0.17	0.09	0.06	0.12	0.07	0.10	0.21	0.25	0.24
		lower	0.34	0.26	0.22	0.20	0.09	0.06	0.12	0.07	0.10	0.21	0.25	0.30
	Normal	higher	0.23	0.17	0.15	0.25	0.09	0.07	0.07	0.09	0.12	0.15	0.19	0.26
		high	0.23	0.17	0.15	0.25	0.09	0.05	0.05	0.07	0.11	0.15	0.19	0.26
		medium	0.23	0.17	0.15	0.13	0.08	0.07	0.13	0.10	0.14	0.18	0.24	0.26
		low	0.30	0.21	0.28	0.26	0.14	0.13	0.25	0.19	0.09	0.20	0.32	0.34
		lower	0.33	0.29	0.33	0.49	0.11	0.13	0.25	0.19	0.15	0.14	0.24	0.40
	Dry	higher	0.26	0.12	0.16	0.15	0.06	0.00	0.03	0.06	0.10	0.16	0.18	0.19
		high	0.26	0.12	0.16	0.15	0.06	0.05	0.04	0.05	0.07	0.10	0.18	0.19
		medium	0.26	0.12	0.16	0.15	0.13	0.11	0.18	0.06	0.13	0.25	0.31	0.22
		low	0.26	0.38	0.32	0.50	0.19	0.11	0.18	0.19	0.20	0.32	0.31	0.25
		lower	0.58	0.46	0.70	0.60	0.19	0.11	0.18	0.19	0.20	0.32	0.50	0.40
	Very	higher	0.44	0.24	0.15	0.07	0.06	0.03	0.07	0.05	0.06	0.11	0.16	0.17
		high	0.44	0.24	0.15	0.07	0.06	0.07	0.04	0.05	0.08	0.11	0.16	0.17
		medium	0.44	0.24	0.15	0.07	0.09	0.03	0.11	0.09	0.10	0.18	0.30	0.27
		low	0.44	0.24	0.15	0.07	0.05	0.03	0.11	0.09	0.10	0.18	0.30	0.50
		lower	0.42	0.35	0.80	0.06	0.05	0.03	0.11	0.09	0.10	0.18	0.30	0.50
Modified general	High	higher	0.21	0.24	0.08	0.17	0.21	0.11	0.09*	0.07*	0.08	0.13	0.17	0.2
		high	0.21	0.24	0.08	0.17	0.21	0.04*	0.08	0.1	0.1	0.14*	0.19*	0.2
		medium	0.23*	0.26*	0.09*	0.19*	0.05*	0.07*	0.12	0.07	0.1	0.15*	0.19	0.22*
		low	0.16*	0.16*	0.17*	0.19*	0.09	0.06	0.12	0.07	0.1	0.21	0.25	0.24
		lower	0.34	0.26	0.22	0.2	0.09	0.06	0.12	0.07	0.1	0.21	0.25	0.3
	Normal	higher	0.23	0.17	0.15	0.25	0.09	0.08*	0.08*	0.1*	0.12	0.15	0.19	0.26
		high	0.23	0.17	0.15	0.25	0.1*	0.05*	0.05*	0.08*	0.12*	0.16*	0.21*	0.26
		medium	0.25*	0.17	0.15	0.14*	0.09*	0.08*	0.13	0.11*	0.15*	0.2*	0.26*	0.28*
		low	0.33*	0.23*	0.31*	0.28*	0.15*	0.13	0.25	0.19	0.09	0.2	0.32	0.34
		lower	0.36*	0.32*	0.36*	0.53*	0.11	0.13	0.25	0.19	0.15	0.14	0.24	0.4
	Dry	higher	0.26	0.12	0.16	0.15	0.06	0.00	0.03	0.06	0.1	0.16	0.18	0.19
		high	0.26	0.12	0.16	0.15	0.06	0.05*	0.04*	0.05*	0.07	0.11*	0.2*	0.19
		medium	0.26	0.12	0.16	0.16*	0.14*	0.11	0.18	0.07*	0.14*	0.27*	0.34*	0.24*
		low	0.28*	0.41*	0.35*	0.55*	0.19	0.11	0.18	0.19	0.2	0.32	0.31	0.25
		lower	0.58	0.46	0.7	0.6	0.19	0.11	0.18	0.19	0.2	0.32	0.5	0.4
	Very	higher	0.44	0.24	0.15	0.07	0.06	0.03	0.07	0.05	0.06	0.11	0.16	0.17
		high	0.44	0.24	0.15	0.07	0.06	0.07	0.04	0.05	0.08	0.11	0.16	0.17
		medium	0.44	0.24	0.15	0.07	0.09	0.03	0.11	0.09	0.1	0.18	0.3	0.27
		low	0.44	0.24	0.15	0.07	0.05	0.03	0.11	0.09	0.1	0.18	0.3	0.5
		lower	0.42	0.35	0.8	0.06	0.05	0.03	0.11	0.09	0.1	0.18	0.3	0.5

Remark : * is the adjusted value.

Table D.9 The adjusted release – antecedent effective storage ratio of Bhumibol Dam

Rule	**Water season**	**Monthly level**	**Releasing ratio (month^{-1})**											
			May	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**
General	High	higher	0.12	0.10	0.17	0.05	0.02	0.07	0.07	0.09	0.13	0.10	0.13	0.12
		high	0.12	0.10	0.17	0.05	0.02	0.01	0.03	0.06	0.09	0.13	0.13	0.12
		medium	0.12	0.10	0.17	0.05	0.02	0.05	0.06	0.06	0.08	0.12	0.16	0.13
		low	0.12	0.10	0.08	0.09	0.05	0.03	0.06	0.06	0.08	0.12	0.21	0.17
		lower	0.12	0.16	0.16	0.12	0.07	0.05	0.06	0.06	0.08	0.12	0.21	0.30
	Normal	higher	0.14	0.09	0.11	0.09	0.12	0.12	0.00	0.04	0.05	0.09	0.13	0.13
		high	0.14	0.09	0.02	0.10	0.04	0.04	0.06	0.09	0.10	0.12	0.18	0.13
		medium	0.14	0.09	0.11	0.09	0.05	0.03	0.07	0.05	0.12	0.17	0.21	0.20
		low	0.18	0.13	0.12	0.15	0.08	0.06	0.07	0.05	0.12	0.17	0.26	0.25
		lower	0.26	0.19	0.24	0.25	0.14	0.16	0.07	0.05	0.12	0.17	0.26	0.33
	Dry	higher	0.23	0.03	0.05	0.01	0.01	0.01	0.09	0.01	0.04	0.11	0.16	0.14
		high	0.23	0.03	0.05	0.01	0.01	0.01	0.09	0.07	0.06	0.11	0.21	0.14
		medium	0.23	0.03	0.05	0.01	0.03	0.03	0.07	0.20	0.14	0.18	0.25	0.31
		low	0.44	0.32	0.25	0.15	0.05	0.17	0.07	0.20	0.14	0.18	0.25	0.35
		lower	0.44	0.53	0.76	0.49	0.26	0.17	0.07	0.20	0.14	0.18	0.25	0.35
	Very Dry	higher	0.34	0.07	0.06	0.05	0.02	0.02	0.15	0.12	0.15	0.17	0.29	0.35
		high	0.34	0.07	0.06	0.05	0.08	0.02	0.15	0.10	0.15	0.17	0.29	0.35
		medium	0.34	0.07	0.06	0.05	0.08	0.02	0.21	0.10	0.15	0.21	0.29	0.35
		low	0.34	0.07	0.40	0.05	0.08	0.02	0.21	0.10	0.15	0.21	0.29	0.30
		lower	0.10	0.28	0.40	0.57	0.08	0.02	0.21	0.10	0.15	0.21	0.29	0.30
Modified general	High	higher	0.12	0.1	0.17	0.05	0.02	0.07	0.07	0.09	0.13	0.1	0.13	0.12
		high	0.12	0.1	0.17	0.05	0.02	0.01	0.04*	0.07*	0.09	0.13	0.13	0.12
		medium	0.12	0.1	0.17	0.05	0.02	0.05	0.06	0.06	0.08	0.12	0.18*	0.15*
		low	0.13*	0.11*	0.08	0.07*	0.05	0.03*	0.06	0.06	0.08	0.12	0.21	0.19*
		lower	0.12	0.16	0.18*	0.13*	0.07	0.05	0.06	0.06	0.08	0.12	0.21	0.3
	Normal	higher	0.14	0.09	0.11	0.09	0.12	0.12	0*	0.04	0.05	0.09	0.13	0.13
		high	0.14	0.09	0.02	0.1	0.04	0.04	0.1*	0.1*	0.1	0.15*	0.18	0.2*
		medium	0.19*	0.11*	0.12*	0.11*	0.05*	0.03*	0.07	0.07*	0.12	0.17	0.21	0.2
		low	0.19*	0.14*	0.15*	0.18*	0.08	0.06	0.07	0.05	0.12	0.17	0.26	0.27*
		lower	0.26	0.21*	0.24	0.29*	0.14*	0.16	0.07	0.05	0.12	0.17	0.26	0.33
	Dry	higher	0.23	0.03	0.05	0.01	0.01	0.01	0.09	0.01	0.04	0.11	0.16	0.14
		high	0.23	0.03	0.05	0.01	0.01	0.01	0.12*	0.08*	0.07*	0.11	0.21	0.14
		medium	0.26*	0.03	0.05	0.01	0.03	0.03	0.07	0.2	0.14	0.18	0.25	0.41*
		low	0.44	0.32	0.32*	0.17*	0.05	0.17	0.07	0.2	0.14	0.18	0.25	0.35
		lower	0.44	0.53	0.76	0.49	0.26	0.17	0.07	0.2	0.14	0.18	0.25	0.35
	Very Dry	higher	0.34	0.07	0.06	0.05	0.02	0.02	0.15	0.12	0.15	0.17	0.29	0.35
		high	0.34	0.07	0.06	0.05	0.08	0.02	0.22*	0.1	0.15	0.17	0.29	0.35
		medium	0.34	0.07	0.06	0.05	0.08	0.02	0.32*	0.13*	0.15	0.21	0.34*	0.35
		low	0.34	0.07	0.4	0.05	0.08	0.02	0.21	0.1	0.15	0.21	0.29	0.3
		lower	0.1	0.28	0.4	0.57	0.08	0.02	0.21	0.1	0.15	0.21	0.29	0.3

Remark : * is the adjusted value.

Table D.10 The correlation of the ANFIS* water release decision making rule for Sirikit Dam

Numbers of MF	Calibration (1987 - 1996)			Verification (1997 - 2011)			Validation (1987 - 2011)		
	R^2	RMSE	SE	R^2	RMSE	SE	R^2	RMSE	SE
3,4,3,4,3	0.75	75	115	0.32	173	194	0.49	188	172
3,4,3,5,4	**0.88**	**51**	**79**	**0.79**	**88**	**109**	**0.84**	**102**	**98**
3,4,4,4,3	0.85	58	90	0.11	206	222	0.36	214	195
3,4,5,4,4	0.86	56	87	0.14	199	220	0.39	206	190
3,4,5,5,3	0.81	65	101	0.3	168	197	0.51	180	171

D.2.6 Evaluation of the efficiency of reservoir operation

Regarding the reservoir operations development processes, the reservoir operations system was developed based on the formulating of release rule, the reservoir operation with the water demand decision making module, the ANFIS* with water demand as a input variable of membership function, the ANFIS* with lateral flow as a input variable of membership function and the ANFIS* with water demand and lateral flow as input variables of membership function. Furthermore, the efficiency of reservoir operation also can be evaluated by comparing the results of reservoir operation with present GCM input variables. The cases of reservoir operation system and the condition can be summarized in Table D.11. From the evaluating results of reservoir operations can be found the effect on the reservoir operation included the storage and the release, the other effect is the water shortage of Phitsanulok and Chao Phraya Irrigation Projects. The efficiency of reservoir operation is evaluated by comparing the operating results with the actual reservoir operation as follows.

1) Comparison of the reservoir release rule shows the results in D.2.6.1
2) Comparison of the reservoir operation with the water demand decision module shows the results in D.2.6.2
3) Comparison of the ANFIS* reservoir operation with actual reservoir operation shows the results in D.2.6.2

4) Comparison of the different reservoir operation by using present GCM hydrological data shows the results in D.2.6.2

Table D.11 The cases of reservoir operation for evaluating the efficiency

Case	Reservoir operation	Condition
Case 1	Actual release	Use all observed input variables
Case 2	General release rule	Use all observed input variables except release
Case 3	Flood release rule	Use all observed input variables except release
Case 4	ANFIS* release rule	Use all observed input variables except release
Case 5	General release rule with water demand module	Use all observed input variables except release and water demand
Case 6	Flood release rule with water demand module	Use all observed input variables except release and water demand
Case 7	ANFIS* release rule with water demand module	Use all observed input variables except release and water demand
Case 8	ANFIS* release rule with water demand as a input variable	Use all observed input variables except release and water demand
Case 9	ANFIS* release rule with lateral flow as a input variable	Use all observed input variables except release and water demand
Case 10	ANFIS* release rule with water demand and lateral flow as the input variables	Use all observed input variables except release and water demand
Case 11	General release rule with water demand module with GCM input variables	Use all present GCM input variables except release and water demand
Case 12	Flood release rule with water demand module with GCM input variables	Use all present GCM input variables except release and water demand
Case 13	ANFIS* release rule with water demand module with GCM input variables	Use all present GCM input variables except release and water demand

D.2.6.1 Comparison of the reservoir release rule

The reservoir release rule which was the first factor of reservoir operation considered to compare. The evaluation of this reservoir release rule was to investigate the efficiency of reservoir operation by using the observed input variables. The comparison of reservoir release rule with the actual reservoir operation in the term of storage, release and water deficit were showed as Table D.12 and D.13 respectively.

Table D.12 The comparison of reservoir release rule in the term of storage and release

Variable	Case study	Season/Annual	Water season							
			High	%Diff	Normal	%Diff	Dry	%Diff	Very dry	%Diff
Storage	Case 1	Wet	7089		5709		5045		3963	
		Dry	9861		8226		7366		7354	
		Annual	8475		6968		6206		5659	
	Case2	Wet	8479	19.61	7301	27.87	6166	22.20	7092	78.95
		Dry	5726	-41.93	4732	-42.47	4429	-39.88	4741	-35.53
		Annual	7103	-16.19	6017	-13.65	5297	-14.64	5917	4.56
	Case 3	Wet	6968	-1.71	6343	11.09	5680	12.57	6194	56.29
		Dry	4312	-56.27	4048	-50.79	3813	-48.24	3869	-47.39
		Annual	5640	-33.45	5195	-25.44	4746	-23.52	5032	-11.08
	Case 4	Wet	8086	14.06	7160	25.40	6055	20.01	7057	78.07
		Dry	4819	-51.13	3998	-51.40	3956	-46.30	4705	-36.02
		Annual	6452	-23.86	5579	-19.93	5005	-19.34	5881	3.93
Release	Case 1	Wet	2986		2312		1603		901	
		Dry	3574		3002		2130		2121	
		Annual	6560		5314		3733		3022	
	Case2	Wet	2892	-3.16	2541	9.91	1682	4.97	998	10.82
		Dry	3284	-8.13	3015	0.44	1919	-9.92	2147	1.22
		Annual	6175	-5.86	5556	4.56	3602	-3.52	3145	4.08
	Case 3	Wet	2989	0.11	2724	17.85	1844	15.04	2021	124.37
		Dry	3718	4.04	2985	-0.55	2396	12.46	2708	27.67
		Annual	6708	2.25	5710	7.45	4240	13.57	4729	56.49
	Case 4	Wet	2445	-18.13	1976	-14.51	1446	-9.80	934	3.72
		Dry	4244	18.76	3915	30.40	2587	21.42	2449	15.45
		Annual	6689	1.97	5891	10.86	4032	8.02	3383	11.96

Table D.13 The comparison of reservoir release rule in the term of % water deficit per demand

Variable	Case study	Season/Annual	Water season							
			High	%Diff	Normal	%Diff	Dry	%Diff	Very dry	%Diff
%Deficit of Phitsanulok Project	Case 1	Wet	3.83		1.29		7.67		26.44	
		Dry	3.64		13.01		17.90		21.74	
		Annual	3.73		7.15		12.79		24.09	
	Case2	Wet	2.77	-1.06	0.70	-0.60	5.58	-2.09	24.19	-2.25
		Dry	3.66	0.02	11.37	-1.64	16.19	-1.71	22.44	0.70
		Annual	3.21	-0.52	6.03	-1.12	10.89	-1.90	23.31	-0.78
	Case 3	Wet	1.62	-2.21	2.70	1.41	8.18	0.51	20.11	-6.33
		Dry	4.91	1.27	13.36	0.34	13.90	-4.00	20.55	-1.19
		Annual	3.27	-0.47	8.03	0.88	11.04	-1.74	20.33	-3.76
	Case 4	Wet	2.04	-1.79	1.65	0.36	5.70	-1.97	25.67	-0.77
		Dry	1.33	-2.31	9.07	-3.95	11.20	-6.71	21.98	0.24
		Annual	1.68	-2.05	5.36	-1.79	8.45	-4.34	23.82	-0.27
%Deficit of Chao Phraya Project	Case 1	Wet	0.99		3.21		10.87		0.00	
		Dry	3.03		5.90		16.91		62.31	
		Annual	2.01		4.55		13.89		31.16	
	Case2	Wet	0.61	-0.37	2.54	-0.67	8.03	-2.85	1.02	1.02
		Dry	1.17	-1.86	4.76	-1.14	4.94	-11.97	31.38	-30.93
		Annual	0.89	-1.12	3.65	-0.90	6.49	-7.41	16.20	-14.96
	Case 3	Wet	0.00	-0.99	5.82	2.62	7.93	-2.94	0.00	0.00
		Dry	0.00	-3.03	1.06	-4.84	5.52	-11.39	32.18	-30.14
		Annual	0.00	-2.01	3.44	-1.11	6.73	-7.17	16.09	-15.07
	Case 4	Wet	0.00	-0.99	3.56	0.35	6.09	-4.78	1.42	1.42
		Dry	1.12	-1.91	3.48	-2.41	2.69	-14.22	27.36	-34.96
		Annual	0.56	-1.45	3.52	-1.03	4.39	-9.50	14.39	-16.77

D.2.6.2 Comparison of the reservoir operation with the water demand decision module

Regarding to the efficiency of reservoir operation, the reservoir operation was developed by adding the water demand decision making module. The objective of this module is to control the water demand according to the storage of reservoir and reduce the water deficit. The comparison of reservoir operation with the water demand decision module in the term of storage, release, water demand and water deficit was shown in Table D.14 to D.16, respectively.

Table D.14 The comparison of reservoir operation with the water demand decision module in the term of storage and release

Variable	Case study	Season/Annual	Water season							
			High	%Diff	Normal	%Diff	Dry	%Diff	Very dry	%Diff
Storage	Case 1	Wet	7089		5709		5045		3963	
		Dry	9861		8226		7366		7354	
		Annual	8475		6968		6206		5659	
	Case 5	Wet	8538	20.45	7370	29.09	6194	22.77	7110	79.38
		Dry	5828	-40.90	4803	-41.61	4459	-39.46	4749	-35.42
		Annual	7183	-15.24	6087	-12.64	5327	-14.17	5930	4.79
	Case 6	Wet	6968	-1.71	6343	11.09	5680	12.57	6194	56.29
		Dry	4312	-56.27	4048	-50.79	3813	-48.24	3869	-47.39
		Annual	5640	-33.45	5195	-25.44	4746	-23.52	5032	-11.08
	Case 7	Wet	8403	18.54	7279	27.50	6145	21.79	7021	77.15
		Dry	5693	-42.27	4567	-44.48	4296	-41.68	4576	-37.77
		Annual	7048	-16.83	5923	-14.99	5221	-15.88	5799	2.48
Release	Case 1	Wet	2986		2312		1603		901	
		Dry	3574		3002		2130		2121	
		Annual	6560		5314		3733		3022	
	Case 5	Wet	2926	-2.01	2533	9.56	1684	5.09	997	10.71
		Dry	3707	3.73	3390	12.91	2172	1.97	2426	14.40
		Annual	6633	1.12	5922	11.45	3857	3.31	3423	13.30
	Case 6	Wet	2989	0.11	2724	17.85	1844	15.04	2021	124.37
		Dry	3718	4.04	2985	-0.55	2396	12.46	2708	27.67
		Annual	6708	2.25	5710	7.45	4240	13.57	4729	56.49
	Case 7	Wet	2890	-3.23	2405	4.05	1565	-2.37	997	10.65
		Dry	3725	4.23	3519	17.23	2285	7.27	2544	19.95
		Annual	6615	0.83	5925	11.50	3850	3.13	3541	17.18

Table D.15 The comparison of reservoir operation with the water demand decision module in the term of water demand

Variable	Case study	Season/ Annual	Water season							
			High	%Diff	Normal	%Diff	Dry	%Diff	Very dry	%Diff
Water demand of Phitsanulok Project	Case 1	Wet	265		281		284		259	
		Dry	555		481		397		419	
		Annual	819		762		681		678	
	Case 5	Wet	218	-17.69	231	-17.59	233	-18.09	218	-16.00
		Dry	510	-7.94	511	6.31	381	-3.95	446	6.31
		Annual	728	-11.09	743	-2.50	614	-9.84	663	-2.21
	Case 6	Wet	228	-13.74	227	-19.14	233	-18.09	218	-16.00
		Dry	487	-12.22	497	3.36	382	-3.80	439	4.74
		Annual	715	-12.71	724	-4.94	615	-9.76	657	-3.18
	Case 7	Wet	219	-17.16	232	-17.31	233	-18.09	218	-16.00
		Dry	506	-8.78	509	5.79	381	-3.95	446	6.31
		Annual	725	-11.48	741	-2.73	614	-9.84	663	-2.21
Water demand of Chao Phraya Project	Case 1	Wet	6104		6569		5134		0	
		Dry	4135		3999		2731		2547	
		Annual	10239		10568		7865		2547	
	Case 5	Wet	6228	2.04	6568	-0.02	5361	4.42	5150	#DIV/0!
		Dry	5253	27.03	5426	35.70	4628	69.48	3703	45.41
		Annual	11481	12.13	11994	13.50	9990	27.01	8853	247.62
	Case 6	Wet	0	-100.00	6771	3.07	5960	16.07	0	#DIV/0!
		Dry	5408	30.77	5328	33.25	5012	83.55	3703	45.41
		Annual	5408	-47.19	12099	14.49	10972	39.50	3703	45.41
	Case 7	Wet	6405	4.93	6625	0.85	5731	11.61	5345	#DIV/0!
		Dry	5057	22.29	5560	39.06	4588	68.00	3703	45.41
		Annual	11462	11.94	12185	15.31	10319	31.19	9048	255.27

Table D.16 The comparison of reservoir operation with the water demand decision module in the term of water deficit per demand

Variable	Case study	Season/ Annual	Water season							
			High	%Diff	Normal	%Diff	Dry	%Diff	Very dry	%Diff
%Deficit of Phitsanulok Project	Case 1	Wet	3.83		1.29		7.67		26.44	
		Dry	3.64		13.01		17.90		21.74	
		Annual	3.73		7.15		12.79		24.09	
	Case 5	Wet	2.87	-0.95	3.19	1.90	9.50	1.83	24.50	-1.94
		Dry	1.77	-1.87	12.37	-0.64	18.23	0.33	22.52	0.78
		Annual	2.32	-1.41	7.78	0.63	13.87	1.08	23.51	-0.58
	Case 6	Wet	4.63	0.80	4.74	3.45	10.52	2.85	22.00	-4.44
		Dry	2.46	-1.18	14.18	1.17	16.27	-1.63	21.82	0.08
		Annual	3.54	-0.19	9.46	2.31	13.39	0.61	21.91	-2.18
	Case 7	Wet	2.54	-1.29	3.16	1.87	9.77	2.10	24.59	-1.85
		Dry	1.06	-2.58	10.88	-2.14	16.53	-1.37	20.79	-0.95
		Annual	1.80	-1.93	7.02	-0.14	13.15	0.37	22.69	-1.40
%Deficit of Chao Phraya Project	Case 1	Wet	0.99		3.21		10.87		0.00	
		Dry	3.03		5.90		16.91		62.31	
		Annual	2.01		4.55		13.89		31.16	
	Case 5	Wet	0.35	-0.63	2.77	-0.44	6.93	-3.95	1.47	1.47
		Dry	0.61	-2.41	7.96	2.06	12.36	-4.55	26.14	-36.17
		Annual	0.48	-1.52	5.37	0.81	9.64	-4.25	13.80	-17.35
	Case 6	Wet	0.00	-0.99	5.03	1.83	8.35	-2.52	0.00	0.00
		Dry	0.00	-3.03	0.19	-5.71	9.48	-7.43	26.17	-36.14
		Annual	0.00	-2.01	2.61	-1.94	8.92	-4.98	13.09	-18.07
	Case 7	Wet	0.00	-0.99	2.45	-0.75	3.83	-7.05	8.84	8.84
		Dry	0.75	-2.28	2.81	-3.09	5.88	-11.03	21.83	-40.48
		Annual	0.37	-1.63	2.63	-1.92	4.85	-9.04	15.34	-15.82

D.2.6.3 Comparison of the ANFIS* reservoir operation with actual reservoir operation

The objective of this issue is to evaluate the effect of input variables for the membership function. The comparison of the results of ANFIS* reservoir operation in the term of storage, release, water demand and water deficit was shown in Table D.17 to D.19, respectively.

Table D.17 The comparison of ANFIS* reservoir operation with actual reservoir operation in the term of storage and release

Variable	Case study	Season/Annual	Water season							
			High	%Diff	Normal	%Diff	Dry	%Diff	Very dry	%Diff
Storage	Case 1	Wet	7089		5709		5045		3963	
		Dry	9861		8226		7366		7354	
		Annual	8475		6968		6206		5659	
	Case 7	Wet	8403	18.54	7279	27.50	6145	21.79	7021	77.15
		Dry	5693	-42.27	4567	-44.48	4296	-41.68	4576	-37.77
		Annual	7048	-16.83	5923	-14.99	5221	-15.88	5799	2.48
	Case 8	Wet	8244	16.29	7188	25.89	6095	20.79	6933	74.94
		Dry	5542	-43.80	4311	-47.59	4124	-44.02	4371	-40.56
		Annual	6893	-18.67	5750	-17.48	5109	-17.67	5652	-0.11
	Case 9	Wet	8297	17.04	7227	26.57	6117	21.23	6944	75.20
		Dry	5604	-43.17	4355	-47.05	4149	-43.68	4389	-40.31
		Annual	6950	-17.99	5791	-16.89	5133	-17.29	5667	0.14
	Case 10	Wet	8423	18.83	7318	28.17	6167	22.24	6959	75.59
		Dry	5761	-41.58	4438	-46.05	4191	-43.11	4412	-40.00
		Annual	7092	-16.32	5878	-15.64	5179	-16.55	5686	0.48
Release	Case 1	Wet	2986		2312		1603		901	
		Dry	3574		3002		2130		2121	
		Annual	6560		5314		3733		3022	
	Case 7	Wet	2890	-3.23	2405	4.05	1565	-2.37	997	10.65
		Dry	3725	4.23	3519	17.23	2285	7.27	2544	19.95
		Annual	6615	0.83	5925	11.50	3850	3.13	3541	17.18
	Case 8	Wet	2844	-4.77	2270	-1.80	1439	-10.21	987	9.64
		Dry	3725	4.23	3665	22.10	2409	13.05	2696	27.14
		Annual	6569	0.14	5935	11.70	3848	3.07	3684	21.92
	Case 9	Wet	2841	-4.87	2274	-1.62	1440	-10.12	988	9.73
		Dry	3708	3.76	3665	22.08	2402	12.72	2688	26.74
		Annual	6549	-0.17	5939	11.77	3842	2.92	3676	21.67
	Case 10	Wet	2825	-5.38	2258	-2.32	1430	-10.78	990	9.95
		Dry	3660	2.40	3683	22.68	2400	12.63	2684	26.55
		Annual	6485	-1.14	5941	11.80	3829	2.58	3674	21.60

Table D.18 The comparison of ANFIS* reservoir operation with actual reservoir operation in the term of water demand

Variable	Case study	Season/Annual	Water season							
			High	%Diff	Normal	%Diff	Dry	%Diff	Very dry	%Diff
Water demand of Phitsanulok Project	Case 1	Wet	265		281		284		259	
		Dry	555		481		397		419	
		Annual	819		762		681		678	
	Case 7	Wet	219	-17.16	232	-17.31	233	-18.09	218	-16.00
		Dry	506	-8.78	509	5.79	381	-3.95	446	6.31
		Annual	725	-11.48	741	-2.73	614	-9.84	663	-2.21
	Case 8	Wet	219	-17.16	232	-17.51	233	-18.09	218	-16.00
		Dry	504	-9.20	509	5.79	381	-3.99	446	6.31
		Annual	723	-11.77	740	-2.80	614	-9.87	663	-2.21
	Case 9	Wet	219	-17.16	232	-17.51	233	-18.09	218	-16.00
		Dry	504	-9.20	509	5.79	381	-3.99	446	6.31
		Annual	723	-11.77	740	-2.80	614	-9.87	663	-2.21
	Case 10	Wet	219	-17.16	232	-17.31	233	-18.09	218	-16.00
		Dry	506	-8.78	509	5.79	381	-3.95	446	6.31
		Annual	725	-11.48	741	-2.73	614	-9.84	663	-2.21
Water demand of Chao Phraya Project	Case 1	Wet	6104		6569		5134		0	
		Dry	4135		3999		2731		2547	
		Annual	10239		10568		7865		2547	
	Case 7	Wet	6405	4.93	6625	0.85	5731	11.61	5345	0.00
		Dry	5057	22.29	5560	39.06	4588	68.00	3703	45.41
		Annual	11462	11.94	12185	15.31	10319	31.19	9048	255.27
	Case 8	Wet	6743	10.47	6578	0.14	5891	14.73	5345	0.00
		Dry	5057	22.29	5556	38.95	4769	74.63	3760	47.63
		Annual	11800	15.24	12134	14.82	10659	35.53	9104	257.49
	Case 9	Wet	6286	2.97	6591	0.34	5832	13.59	5345	0.00
		Dry	5231	26.50	5467	36.71	4769	74.63	3760	47.63
		Annual	11517	12.48	12058	14.10	10601	34.78	9104	257.49
	Case 10	Wet	6405	4.93	6625	0.85	5731	11.61	5345	0.00
		Dry	5057	22.29	5560	39.06	4667	70.91	3760	47.63
		Annual	11462	11.94	12185	15.31	10398	32.20	9104	257.49

Table D.19 The comparison of ANFIS* reservoir operation with actual reservoir operation in the term of water deficit

Variable	Case study	Season/Annual	Water season							
			High	%Diff	Normal	%Diff	Dry	%Diff	Very dry	%Diff
%Deficit of Phitsanulok Project	Case 1	Wet	3.83		1.29		7.67		26.44	
		Dry	3.64		13.01		17.90		21.74	
		Annual	3.73		7.15		12.79		24.09	
	Case 7	Wet	2.54	-1.29	3.16	1.87	9.77	2.10	24.59	-1.85
		Dry	1.06	-2.58	10.88	-2.14	16.53	-1.37	20.79	-0.95
		Annual	1.80	-1.93	7.02	-0.14	13.15	0.37	22.69	-1.40
	Case 8	Wet	2.26	-1.57	2.97	1.68	10.15	2.48	24.69	-1.75
		Dry	0.47	-3.17	9.46	-3.56	14.99	-2.91	18.69	-3.05
		Annual	1.37	-2.37	6.21	-0.94	12.57	-0.21	21.69	-2.40
	Case 9	Wet	2.19	-1.64	2.90	1.60	10.02	2.35	24.56	-1.88
		Dry	0.50	-3.14	9.31	-3.71	14.92	-2.99	18.71	-3.03
		Annual	1.35	-2.39	6.10	-1.05	12.47	-0.32	21.64	-2.45
	Case 10	Wet	2.01	-1.81	2.71	1.41	9.72	2.05	24.22	-2.21
		Dry	0.52	-3.12	8.81	-4.20	14.47	-3.43	18.54	-3.20
		Annual	1.27	-2.47	5.76	-1.39	12.10	-0.69	21.38	-2.71
%Deficit of Chao Phraya Project	Case 1	Wet	0.99		3.21		10.87		0.00	
		Dry	3.03		5.90		16.91		62.31	
		Annual	2.01		4.55		13.89		31.16	
	Case 7	Wet	0.00	-0.99	2.45	-0.75	3.83	-7.05	8.84	8.84
		Dry	0.75	-2.28	2.81	-3.09	5.88	-11.03	21.83	-40.48
		Annual	0.37	-1.63	2.63	-1.92	4.85	-9.04	15.34	-15.82
	Case 8	Wet	0.00	-0.99	2.43	-0.78	2.98	-7.89	9.33	9.33
		Dry	0.77	-2.26	1.65	-4.25	8.16	-8.75	17.51	-44.80
		Annual	0.38	-1.62	2.04	-2.52	5.57	-8.32	13.42	-17.73
	Case 9	Wet	0.09	-0.90	3.43	0.23	3.56	-7.32	9.10	9.10
		Dry	0.95	-2.08	2.61	-3.29	7.70	-9.21	17.49	-44.82
		Annual	0.52	-1.49	3.02	-1.53	5.63	-8.26	13.30	-17.86
	Case 10	Wet	0.04	-0.94	2.61	-0.60	2.72	-8.15	8.79	8.79
		Dry	0.83	-2.19	2.87	-3.03	6.45	-10.46	17.38	-44.94
		Annual	0.44	-1.57	2.74	-1.81	4.58	-9.31	13.09	-18.07

D.2.6.4 Comparison of the different reservoir operation by using present GCM hydrological data

The objective of this issue is to compare the results of observed and GCM hydrological input variables. The comparison of the results of different reservoir operations in the term of storage, release, water demand and water deficit per demand was shown in Table D.20 to D.22, respectively.

Table D.20 The comparison of different reservoir operations in the term of storage and release

Variable	Case study	Season/ Annual	Water season							
			High	%Diff	Normal	%Diff	Dry	%Diff	Very dry	%Diff
Storage (MCM)	Case 1	Wet	7089		5709		5045		3963	
		Dry	9861		8226		7366		7354	
		Annual	8475		6968		6206		5659	
	Case 11	Wet	9202	29.81	7746	35.68	6024	19.41	N.O.	N.O.
		Dry	6109	-38.05	4870	-40.80	4425	-39.93	N.O.	N.O.
		Annual	7655	-9.68	6308	-9.47	5224	-15.82	N.O.	N.O.
	Case 12	Wet	N.O.	N.O.	6866	20.27	6537	29.57	N.O.	N.O.
		Dry	N.O.	N.O.	4270	-48.09	3953	-46.33	N.O.	N.O.
		Annual	N.O.	N.O.	5568	-20.09	5245	-15.49	N.O.	N.O.
	Case 13	Wet	N.O.	N.O.	8033	40.71	7098	40.69	5946	50.04
		Dry	4032	-59.11	3770	-54.17	3750	-49.09	N.O.	N.O.
		Annual	2016	-76.21	5902	-15.30	5424	-12.60	2973	-47.46
Release (MCM)	Case 1	Wet	2986		2312		1603		901	
		Dry	3574		3002		2130		2121	
		Annual	6560		5314		3733		3022	
	Case 11	Wet	2580	-13.60	2458	6.31	1675	4.49	N.O.	N.O.
		Dry	3874	8.39	3482	15.99	2185	2.58	N.O.	N.O.
		Annual	6454	-1.62	5940	11.78	3860	3.40	N.O.	N.O.
	Case 12	Wet	N.O.	N.O.	2889	24.96	2448	52.71	N.O.	N.O.
		Dry	N.O.	N.O.	3815	27.08	2833	33.00	N.O.	N.O.
		Annual	N.O.	N.O.	6704	26.16	5282	41.49	N.O.	N.O.
	Case 13	Wet	N.O.	N.O.	2461	6.44	1904	18.78	767	-14.87
		Dry	4713	31.87	4533	51.00	2994	40.56	N.O.	N.O.
		Annual	4713	-28.16	6994	31.61	4897	31.18	767	-74.62

Remark : N.O. is no occurrence

Table D.20 The comparison of different reservoir operations in the term of water demand

Variable	Case study	Season/ Annual	Water season							
			High	%Diff	Normal	%Diff	Dry	%Diff	Very dry	%Diff
Water demand of Phitsanulok Project (MCM)	Case 1	Wet	265		281		284		259	
		Dry	555		481		397		419	
		Annual	819		762		681		678	
	Case 11	Wet	275	3.77	276	-1.78	281	-1.06	N.O.	N.O.
		Dry	612	10.27	634	31.81	606	52.64	N.O.	N.O.
		Annual	886	8.18	910	19.42	886	30.10	N.O.	N.O.
	Case 12	Wet	N.O.	N.O.	281	0.00	274	-3.52	N.O.	N.O.
		Dry	N.O.	N.O.	641	33.26	576	45.09	N.O.	N.O.
		Annual	N.O.	N.O.	923	21.13	849	24.67	N.O.	N.O.
	Case 13	Wet	N.O.	N.O.	272	-3.20	276	-2.82	275	6.18
		Dry	689	24.14	635	32.02	610	53.65	N.O.	N.O.
		Annual	689	-15.87	906	18.90	886	30.10	275	-59.44
Water demand of Chao Phraya Project (MCM)	Case 1	Wet	6104		6569		5134		0	
		Dry	4135		3999		2731		2547	
		Annual	10239		10568		7865		2547	
	Case 11	Wet	5578	-8.62	5739	-12.64	5575	8.59	N.O.	N.O.
		Dry	4335	4.84	4278	6.98	4600	68.44	N.O.	N.O.
		Annual	9913	-3.18	10017	-5.21	10175	29.37	N.O.	N.O.
	Case 12	Wet	N.O.	N.O.	5820	-11.40	5585	8.78	N.O.	N.O.
		Dry	N.O.	N.O.	4087	2.20	4693	71.84	N.O.	N.O.
		Annual	N.O.	N.O.	9906	-6.26	10279	30.69	N.O.	N.O.
	Case 13	Wet	N.O.	N.O.	5768	-12.19	5350	4.21	5993	N.O.
		Dry	3431	-17.03	3840	-3.98	4448	62.87	N.O.	N.O.
		Annual	3431	-66.49	9608	-9.08	9798	24.58	5993	135.30

Remark : N.O. is no occurrence

Table D.21 The comparison of different reservoir operations in the term of water deficit per demand

Variable	Case study	Season/ Annual	Water season							
			High	%Diff	Normal	%Diff	Dry	%Diff	Very dry	%Diff
%Deficit of Phitsanulok Project (%)	Case 1	Wet	3.83		1.29		7.67		26.44	
		Dry	3.64		13.01		17.9		21.74	
		Annual	3.73		7.15		12.79		24.09	
	Case 11	Wet	8.16	4.33	6.32	5.03	11.62	3.95	N.O.	N.O.
		Dry	7.18	3.54	14.02	1.01	32.58	14.68	N.O.	N.O.
		Annual	7.67	3.94	10.17	3.02	22.1	9.31	N.O.	N.O.
	Case 12	Wet	N.O.	N.O.	7.23	5.94	8.38	0.71	N.O.	N.O.
		Dry	N.O.	N.O.	10.61	-2.40	29.53	11.63	N.O.	N.O.
		Annual	N.O.	N.O.	8.92	1.77	18.96	6.17	N.O.	N.O.
	Case 13	Wet	N.O.	N.O.	4.78	3.49	8.87	1.20	39.51	13.07
		Dry	0.62	-3.02	8.05	-4.96	23.01	5.11	N.O.	N.O.
		Annual	0.31	-3.42	6.41	-0.74	15.94	3.15	19.75	-4.34
%Deficit of Chao Phraya Project (%)	Case 1	Wet	0.99		3.21		10.87		N.O.	
		Dry	3.03		5.9		16.91		62.31	
		Annual	2.01		4.55		13.89		31.16	
	Case 11	Wet	0.44	-0.55	0.65	-2.56	2.15	-8.72	N.O.	N.O.
		Dry	0.1	-2.93	1.29	-4.61	9.92	-6.99	N.O.	N.O.
		Annual	0.27	-1.74	0.97	-3.58	6.04	-7.85	N.O.	N.O.
	Case 12	Wet	N.O.	N.O.	2.22	-0.99	3.98	-6.89	N.O.	N.O.
		Dry	N.O.	N.O.	0.33	-5.57	5.52	-11.39	N.O.	N.O.
		Annual	N.O.	N.O.	1.28	-3.27	4.75	-9.14	N.O.	N.O.
	Case 13	Wet	N.O.	N.O.	0.98	-2.23	0.92	-9.95	2.72	N.O.
		Dry	N.O.	N.O.	1.35	-4.55	7.26	-9.65	N.O.	N.O.
		Annual	N.O.	N.O.	1.16	-3.39	4.09	-9.80	1.36	-29.80

Remark : N.O. is no occurrence

Appendix E

Input variables for the reservoir operation model

Table E.1 Cultivated area in Phisanulok and Great Chao Phraya Irrigation Project

Year	Phitsanulok Irrigation Project				Great Chao Phraya Irrigation Project			
	Wet		Dry		Wet		Dry	
	Major rice planting area (rais)	Crop-vegetable planting area (rais)	Second rice planting area (rais)	Crop-vegetable planting area (rais)	Major rice planting area (rais)	Crop-vegetable planting area (rais)	Second rice planting area (rais)	Crop-vegetable planting area (rais)
1978	575,527	29,479	501,606	22,499	N/A	N/A	2,126,511	17,164
1979	591,007	29,479	230,098	10,321	6,110,011	40,275	3,036,069	24,506
1980	563,643	29,479	465,710	20,889	6,063,196	39,966	1,336,388	10,787
1981	587,390	29,479	507,437	22,760	6,151,816	40,550	3,146,478	25,397
1982	549,750	29,479	430,140	19,293	5,971,661	39,363	3,271,148	26,403
1983	553,170	29,479	440,695	19,767	6,177,543	40,720	3,181,418	25,679
1984	575,690	29,479	455,688	20,439	6,211,338	40,942	3,083,767	24,891
1985	519,358	29,479	153,106	1,819	6,224,301	41,028	2,857,049	23,061
1986	606,274	29,479	122,276	1,216	6,013,172	39,636	2,737,061	22,092
1987	607,829	29,479	134,617	8,469	6,044,620	39,844	2,452,946	19,799
1988	624,574	29,479	173,265	5,871	5,803,036	38,251	2,478,542	20,006
1989	631,993	29,479	366,479	27,284	6,049,469	39,875	2,747,306	22,175
1990	583,256	29,479	320,000	19,873	5,825,102	38,397	2,913,505	23,517
1991	609,045	29,479	234,473	21,533	5,623,723	37,069	1,761,507	14,218
1992	510,925	29,479	436,693	13,019	5,619,457	37,041	2,050,005	16,547
1993	563,024	29,479	139,215	12,770	5,671,322	37,383	1,855,854	14,980
1994	519,764	29,479	111,156	46,469	5,335,464	35,169	1,649,177	13,312
1995	503,459	29,479	324,186	52,375	5,281,423	34,813	2,440,705	19,700
1996	587,289	29,479	508,914	346	5,810,937	38,303	2,978,486	24,041
1997	606,142	29,479	530,914	68	5,873,787	38,717	2,870,309	23,168
1998	574,915	29,479	216,254	86	4,498,671	25,066	3,279,054	32,827
1999	537,882	29,479	443,713	1,296	4,757,635	25,369	2,718,853	38,268
2000	585,602	29,479	533,360	500	5,007,553	22,643	3,893,337	30,098
2001	586,484	29,479	623,131	0	4,767,729	23,056	3,982,703	23,083
2002	552,606	29,479	600,737	0	4,705,732	22,784	4,352,867	30,357
2003	531,620	29,479	626,670	650	4,705,240	25,548	4,224,983	23,897
2004	535,250	29,479	600,000	0	4,723,857	22,893	4,076,616	30,735
2005	528,905	29,479	610,200	0	4,696,820	25,105	4,175,344	24,735
2006	553,353	29,479	615,031	0	4,855,087	25,603	4,245,109	17,906
2007	559,785	29,479	624,382	0	4,708,558	24,746	4,649,456	21,250
2008	521,388	29,479	610,621	0	4,982,689	31,389	4,788,473	25,535
2009	564,806	29,479	598,393	0	5,151,903	64,916	4,677,382	66,479
2010	526,757	29,479	614,799	0	4,901,653	69,392	5,027,485	65,781
2011	648,294	29,479	682,162	0	5,470,217	40,348	5,169,949	40,396
2012	570,792	29,479	759,606	0	5,154,395	32,906	4,740,301	45,253

Table E.2 Cultivated area of major rice crop of the Phisanulok Irrigation Project in rainy season

Year	Cultivated area (rais)						
	L001	L002	L003	L004	L005	L006	TOTAL
1979	84,998	181,000	20,095	173,276	126,213	5,425	591,007
1980	81,063	172,619	19,165	165,253	120,369	5,174	563,643
1981	84,478	179,892	19,972	172,216	125,441	5,392	587,390
1982	79,065	168,364	18,692	161,180	117,402	5,046	549,750
1983	79,557	169,412	18,809	162,183	118,133	5,078	553,170
1984	82,795	176,309	19,574	168,786	122,942	5,284	575,690
1985	74,694	159,057	17,659	152,270	110,912	4,767	519,358
1986	87,194	185,675	20,614	177,752	129,473	5,565	606,274
1987	87,418	186,151	20,667	178,208	129,806	5,579	607,829
1988	89,826	191,280	21,236	183,118	133,382	5,733	624,574
1989	90,893	193,552	21,489	185,293	134,966	5,801	631,993
1990	83,883	178,626	19,831	171,004	124,558	5,354	583,256
1991	87,592	186,524	20,708	178,565	130,065	5,590	609,045
1992	73,481	156,474	17,372	149,797	109,111	4,690	510,925
1993	80,974	172,430	19,144	165,072	120,237	5,168	563,024
1994	74,752	159,181	17,673	152,389	110,999	4,771	519,764
1995	72,407	154,187	17,118	147,608	107,517	4,621	503,459
1996	84,463	179,861	19,969	172,186	125,419	5,391	587,289
1997	87,175	185,635	20,610	177,714	129,445	5,564	606,142
1998	82,070	176,687	7,469	186,000	118,447	4,243	574,915
1999	80,521	166,553	11,339	156,780	118,447	4,243	537,882
2000	87,405	178,322	29,521	167,660	119,286	3,408	585,602
2001	86,680	174,996	28,306	174,400	119,387	2,715	586,484
2002	91,000	172,508	17,973	164,435	99,217	7,473	552,606
2003	83,213	158,788	17,331	166,620	104,580	1,088	531,620
2004	63,951	166,097	14,739	160,635	125,644	4,184	535,250
2005	78,570	162,573	20,244	153,550	104,715	9,253	528,905
2006	89,050	149,686	18,434	143,612	145,165	7,406	553,353
2007	55,220	192,410	23,229	152,448	129,580	6,898	559,785
2008	74,986	159,678	17,728	152,865	111,346	4,786	521,388
2009	81,230	172,975	19,204	165,594	120,618	5,184	564,806
2010	75,758	161,323	17,910	154,439	112,492	4,835	526,757
2011	93,237	198,544	22,043	190,072	138,447	5,951	648,294
2012	82,091	174,809	19,408	167,350	121,896	5,239	570,792

Remark : L001 : Naraesuen Dam O&M Project, Phrom Phiram, Phisanulok
L002 : Plaichumpol O&M Project, Maung Phisanulok, Phisanulok
L003 : Plaichumpol O&M Project, Muang Phichit, Phichit
L004 : Dong Setti O&M Project, Muang Phichit, Phichit
L005 : Tha Bua O&M Project, Pho Talae, Phichit
L006 : Tha Bua O&M Project, Muang Nakhon Sawan, Nakhon Sawan

Table E.3 Cultivated area of second rice crop the Phisanulok Irrigation Project in dry season

Year	Cultivated area (rais)						
	L001	L002	L003	L004	L005	L006	TOTAL
1979	28,830	62,993	9,853	65,036	59,592	3,795	230,098
1980	58,350	127,495	19,942	131,631	120,612	7,680	465,710
1981	63,578	138,918	21,729	143,425	131,418	8,369	507,437
1982	53,894	117,757	18,419	121,577	111,399	7,094	430,140
1983	55,216	120,647	18,871	124,561	114,133	7,268	440,695
1984	57,095	124,751	19,513	128,798	118,016	7,515	455,688
1985	19,183	41,915	6,556	43,275	39,652	2,525	153,106
1986	15,320	33,475	5,236	34,561	31,668	2,017	122,276
1987	16,867	36,853	5,764	38,049	34,864	2,220	134,617
1988	21,709	47,434	7,419	48,973	44,873	2,857	173,265
1989	45,917	100,329	15,693	103,584	94,912	6,044	366,479
1990	40,094	87,605	13,703	90,447	82,875	5,277	320,000
1991	29,378	64,190	10,040	66,273	60,725	3,867	234,473
1992	54,715	119,551	18,700	123,429	113,097	7,202	436,693
1993	17,443	38,112	5,961	39,348	36,054	2,296	139,215
1994	13,927	30,431	4,760	31,418	28,788	1,833	111,156
1995	40,618	88,751	13,882	91,630	83,959	5,346	324,186
1996	63,763	139,322	21,792	143,842	131,801	8,393	508,914
1997	66,520	145,345	22,734	150,060	137,498	8,756	530,914
1998	27,095	59,203	9,260	61,123	56,006	3,566	216,254
1999	22,976	105,960	15,433	133,680	155,692	9,972	443,713
2000	86,230	125,893	18,336	179,000	150,428	9,634	569,521
2001	83,235	181,340	26,412	153,020	151,455	9,700	605,162
2002	66,375	171,757	25,016	178,730	149,297	9,562	600,737
2003	83,991	178,419	29,724	171,000	153,549	9,384	626,067
2004	67,173	167,265	28,578	172,125	152,196	9,445	596,782
2005	75,874	159,455	29,273	170,940	149,668	9,497	594,707
2006	86,478	177,080	28,907	170,386	142,740	9,431	615,022
2007	90,200	180,459	26,284	170,491	147,501	9,447	624,382
2008	76,507	167,166	26,147	172,589	158,141	10,070	610,621
2009	74,975	163,819	25,624	169,133	154,974	9,869	598,393
2010	77,030	168,310	26,326	173,770	159,223	10,139	614,799
2011	85,470	186,752	29,211	192,810	176,669	11,250	682,162
2012	95,174	207,953	32,527	214,699	196,726	12,527	759,606

Remark : L001 : Naraesuen Dam O&M Project, Phrom Phiram, Phisanulok
L002 : Plaichumpol O&M Project, Maung Phisanulok, Phisanulok
L003 : Plaichumpol O&M Project, Muang Phichit, Phichit
L004 : Dong Setti O&M Project, Muang Phichit, Phichit
L005 : Tha Bua O&M Project, Pho Talae, Phichit
L006 : Tha Bua O&M Project, Muang Nakhon Sawan, Nakhon Sawan

Table E.4 Cultivated area of upland crop of the Phisanulok Irrigation Project in rainy season

Year	Cultivated area (rais)						
	L001	L002	L003	L004	L005	L006	TOTAL
1979	59	0	29,420	0	0	0	29,479
1980	59	0	29,420	0	0	0	29,479
1981	59	0	29,420	0	0	0	29,479
1982	59	0	29,420	0	0	0	29,479
1983	59	0	29,420	0	0	0	29,479
1984	59	0	29,420	0	0	0	29,479
1985	59	0	29,420	0	0	0	29,479
1986	59	0	29,420	0	0	0	29,479
1987	59	0	29,420	0	0	0	29,479
1988	59	0	29,420	0	0	0	29,479
1989	59	0	29,420	0	0	0	29,479
1990	59	0	29,420	0	0	0	29,479
1991	59	0	29,420	0	0	0	29,479
1992	59	0	29,420	0	0	0	29,479
1993	59	0	29,420	0	0	0	29,479
1994	59	0	29,420	0	0	0	29,479
1995	59	0	29,420	0	0	0	29,479
1996	59	0	29,420	0	0	0	29,479
1997	59	0	29,420	0	0	0	29,479
1998	59	0	29,420	0	0	0	29,479
1999	59	0	29,420	0	0	0	29,479
2000	59	0	29,420	0	0	0	29,479
2001	59	0	29,420	0	0	0	29,479
2002	59	0	29,420	0	0	0	29,479
2003	59	0	29,420	0	0	0	29,479
2004	59	0	29,420	0	0	0	29,479
2005	59	0	29,420	0	0	0	29,479
2006	59	0	29,420	0	0	0	29,479
2007	59	0	29,420	0	0	0	29,479
2008	59	0	29,420	0	0	0	29,479

Remark : L001 : Naraesuen Dam O&M Project, Phrom Phiram, Phisanulok
L002 : Plaichumpol O&M Project, Maung Phisanulok, Phisanulok
L003 : Plaichumpol O&M Project, Muang Phichit, Phichit
L004 : Dong Setti O&M Project, Muang Phichit, Phichit
L005 : Tha Bua O&M Project, Pho Talae, Phichit
L006 : Tha Bua O&M Project, Muang Nakhon Sawan, Nakhon Sawan

Table E.5 Cultivated area of upland crop the Phisanulok Irrigation Project in dry season

Year	Cultivated area (rais)						
	L001	L002	L003	L004	L005	L006	TOTAL
1979	763	47	29,467	509	266	36	31,087
1980	763	47	29,467	509	266	36	31,087
1981	763	47	29,467	509	266	36	31,087
1982	763	47	29,467	509	266	36	31,087
1983	763	47	29,467	509	266	36	31,087
1984	763	47	29,467	509	266	36	31,087
1985	763	47	29,467	509	266	36	31,087
1986	763	47	29,467	509	266	36	31,087
1987	763	47	29,467	509	266	36	31,087
1988	763	47	29,467	509	266	36	31,087
1989	763	47	29,467	509	266	36	31,087
1990	763	47	29,467	509	266	36	31,087
1991	763	47	29,467	509	266	36	31,087
1992	763	47	29,467	509	266	36	31,087
1993	763	47	29,467	509	266	36	31,087
1994	763	47	29,467	509	266	36	31,087
1995	763	47	29,467	509	266	36	31,087
1996	763	47	29,467	509	266	36	31,087
1997	763	47	29,467	509	266	36	31,087
1998	763	5	29,425	509	56	36	30,794
1999	1,025	134	29,554	509	266	36	31,523
2000	500	2	29,422	509	266	36	30,734
2001	763	47	29,467	509	266	36	31,087
2002	763	47	29,467	509	266	36	31,087
2003	763	47	29,467	650	266	36	31,228
2004	763	47	29,467	368	476	36	31,156
2005	763	47	29,467	509	266	36	31,087
2006	763	47	29,467	509	266	36	31,087
2007	763	47	29,467	509	266	36	31,087
2008	763	47	29,467	509	266	36	31,087

Remark : L001 : Naraesuen Dam O&M Project, Phrom Phiram, Phisanulok
L002 : Plaichumpol O&M Project, Maung Phisanulok, Phisanulok
L003 : Plaichumpol O&M Project, Muang Phichit, Phichit
L004 : Dong Setti O&M Project, Muang Phichit, Phichit
L005 : Tha Bua O&M Project, Pho Talae, Phichit
L006 : Tha Bua O&M Project, Muang Nakhon Sawan, Nakhon Sawan

Table E.6 Actual water allocation in Phisanulok Irrigation Project

Year	Actual water allocation (MCM/month)												Annual
	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	(MCM)
1982	41.3	36.5	4.4	40.6	86.3	94.1	92.7	39.5	3.4	6.7	26.3	40.	534.4
1983	36.6	32.0	14.6	82.9	96.7	78.7	89.2	24.3	5.9	6.0	57.1	68.	534.3
1984	72.7	45.1	0.0	52.4	125.4	133.9	121.6	55.7	2.0	7.4	54.4	73.	740.0
1985	75.7	43.3	0.0	28.2	82.4	103.2	83.4	56.8	0.7	2.7	61.2	73.	609.2
1986	78.3	31.0	6.7	60.7	151.8	181.3	204.9	125.5	0.0	7.1	51.4	100	977.7
1987	97.8	77.4	26.6	111.0	114.7	182.1	174.4	77.9	0.0	0.0	42.5	81.	1,020.
1988	78.7	28.0	0.9	96.3	158.5	170.1	173.7	118.2	0.0	20.0	121.3	156	948.8
1989	150.9	92.8	1.4	44.8	158.8	188.9	162.8	125.1	6.4	18.6	64.2	133	1,229.
1990	145.4	67.8	0.0	41.6	173.5	194.9	201.7	111.7	5.0	22.1	73.0	109	1,158.
1991	100.6	50.3	3.6	15.2	88.4	156.6	161.0	126.4	4.6	13.0	76.6	136	910.9
1992	132.5	113.1	16.0	0.0	49.9	84.6	116.4	111.8	15.2	3.0	0.5	5.3	865.7
1993	8.2	0.0	0.5	84.6	147.6	129.8	97.5	81.7	13.6	4.4	7.0	0.9	572.3
1994	0.0	0.0	0.0	7.9	123.9	74.7	121.6	85.0	11.1	46.0	93.7	143	436.5
1995	85.3	22.4	0.0	40.5	52.4	2.1	12.4	12.7	0.0	76.1	162.3	196	511.1
1996	126.5	47.3	4.8	49.4	1,402.4	994.9	91.7	37.2	19.0	109.1	169.5	131	3,208.
1997	148.1	54.1	6.1	141.9	125.8	138.3	133.9	97.9	11.7	105.2	105.9	135	1,267.
1998	119.1	41.5	0.0	32.0	172.2	140.2	94.1	21.5	11.0	35.0	52.0	59.	978.4
1999	44.3	0.0	0.0	30.5	76.3	59.3	82.7	51.2	35.3	80.6	134.7	148	526.7
2000	127.0	279.0	0.0	16.8	100.4	49.8	92.0	103.7	65.1	93.9	151.0	114	1,197.
2001	152.0	35.3	20.9	69.6	95.0	56.9	55.0	79.1	16.9	62.4	153.7	145	940.3
2002	157.8	129.1	18.7	127.3	94.5	3.0	24.0	1.2	62.3	166.5	137.2	136	979.5
2003	145.7	125.1	10.1	67.5	129.7	79.9	110.6	66.5	0.0	68.5	141.8	95.	1,174.
2004	76.6	84.7	0.0	63.2	71.0	70.7	125.9	0.0	0.0	131.6	116.8	112	798.1
2005	100.4	54.7	116.4	103.8	94.9	33.3	86.2	0.0	0.0	0.0	0.0	3.9	950.3
2006	15.1	12.9	34.2	61.7	101.7	31.1	44.8	42.4	118.7	163.4	171.9	192	466.3
2007	109.7	29.9	60.5	99.4	119.9	63.1	65.3	73.7	134.5	142.4	161.4	193	1,283.
2008	131.0	117.7	163.1	142.1	137.1	51.8	0.0	97.3	163.1	166.3	175.1	187	1,501.
Max	157.8	279.0	163.1	142.1	1,402.4	994.9	204.9	126.4	163.1	166.5	175.1	196	3,208.
Min	0.0	0.0	0.0	0.0	49.9	2.1	0.0	0.0	0.0	0.0	0.0	0.9	436.5
Mean	94.7	61.1	18.9	63.4	160.4	131.4	104.4	67.6	26.1	57.7	94.9	110	974.8

Table E.7 Actual water allocation in Great Chao Phraya Irrigation Project

Year	Actual water allocation (MCM/month)												Annual (MCM)
	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	
1979	1379	1213	1001	1243	1503	1506	1516	1379	715	343	215	356	12369
1980	368	600	754	1235	1650	1630	1786	1135	386	394	617	895	11450
1981	1122	1136	1065	951	1353	1680	2089	1973	522	536	806	1347	14580
1982	1166	697	718	916	1267	1703	2290	1921	587	520	885	1216	13886
1983	1275	1138	700	662	945	1703	1181	863	391	295	687	1262	11102
1984	1153	962	897	637	1136	2040	2279	2110	978	450	750	1245	14637
1985	1182	873	718	1039	1578	1472	1784	1677	493	324	697	1142	12979
1986	1063	860	1024	991	1042	1581	1805	1602	870	321	798	1095	13052
1987	1032	836	671	560	1039	897	1623	1661	726	262	363	895	10565
1988	793	852	669	809	1015	1192	1205	1299	753	455	605	908	10555
1989	1024	980	835	707	1029	1335	1620	1654	771	386	462	924	11727
1990	923	836	923	948	1010	1602	680	1205	876	370	402	720	10495
1991	715	445	389	225	817	1405	1489	1288	726	321	341	434	8595
1992	407	391	137	82	961	756	1643	1381	707	268	314	470	7517
1993	486	509	620	450	683	1048	1018	616	489	96	132	156	6303
1994	104	525	1011	878	1375	1618	1475	1398	1051	383	551	960	11329
1995	1080	1077	887	945	1098	816	1130	845	771	685	942	1564	11840
1996	1351	675	672	1081	1194	1173	1039	1072	859	644	900	1171	11831
1997	1167	1047	841	828	1098	1013	1565	1339	967	451	565	793	11674
1998	801	613	385	728	918	1364	1494	974	558	221	251	254	8561
1999	247	155	529	752	1094	1033	1271	1070	1095	435	711	892	9284
2000	657	866	758	815	890	1070	1150	1587	968	706	899	988	11354
2001	987	1016	801	1116	1050	1419	1387	1346	1072	706	760	1140	12800
2002	1103	993	986	1000	1194	1196	1541	888	900	890	1034	1158	12883
2003	948	1137	1075	819	927	973	1292	1408	886	584	717	769	11535
2004	684	694	674	888	735	1052	1142	1568	1000	432	679	896	10444
2005	666	833	764	806	874	1052	1142	1568	1000	670	634	657	10666
2006	663	621	737	921	1184	1126	1879	836	968	997	979	1015	11926
2007	939	687	1023	1065	1179	911	1373	1262	875	432	711	892	11349
2008	657	754	656	881	893	782	1402	1365	988	985	905	1029	11296
2009	967	779	947	981	1002	913	1047	1197	882	898	781	822	11216
2010	464	334	276	280	852	822	867	1048	960	889	861	925	8579
2011	588	770	1104	1062	1270	1274	1936	623	864	1318	1112	1263	13184
2012	982	1167	1035	1021	872	627	759	861	867	875	692	405	10164
Max	1379	1213	1104	1243	1864	2110	2290	2110	1095	1318	1112	1564	14637
Min	104	155	137	82	683	627	680	616	241	96	132	156	6303
Mean	777	722	751	868	1205	1373	1559	1373	700	471	586	816	11200

Table E.8 Monthly mean runoff of station C.13

Year	Actual water allocation (MCM/month)												Annual (MCM)
	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	
1979	238	385	1035	422	331	598	870	191	435	197	143	80	4925
1980	173	408	1161	995	1720	3420	8626	2429	840	319	308	336	20735
1981	304	585	1183	1298	3124	2599	886	2160	1611	445	269	305	14769
1982	328	288	293	302	312	1127	1854	594	659	270	240	270	6537
1983	268	257	310	213	917	1508	5400	5571	1608	342	235	269	16898
1984	279	253	647	496	239	539	974	360	292	222	211	239	4751
1985	262	261	258	273	254	1440	3173	3318	2158	282	224	249	12152
1986	252	1609	1201	634	716	850	351	253	417	217	224	264	6988
1987	225	225	209	179	200	2005	2486	416	539	163	169	239	7055
1988	140	561	953	835	700	2026	3829	1864	544	212	127	168	11959
1989	231	230	973	245	213	493	985	333	399	136	121	250	4609
1990	243	400	1489	279	246	434	2161	529	412	179	175	211	6758
1991	195	133	112	115	511	1484	1037	242	223	123	148	184	4507
1992	229	226	166	143	642	254	1862	525	369	198	214	280	5108
1993	241	237	380	163	178	727	492	131	157	140	141	184	3171
1994	137	269	1720	1361	1089	3808	3918	186	356	155	195	203	13397
1995	143	255	493	501	2652	6776	10034	3915	866	143	162	223	26163
1996	254	1453	1733	507	1153	3362	7251	5425	1480	96	108	122	22944
1997	123	119	95	85	92	992	1367	106	88	72	131	207	3477
1998	257	195	99	649	244	392	888	122	98	111	160	185	3400
1999	198	1986	1546	217	306	2423	4888	5347	653	136	200	258	18158
2000	346	1035	1584	1250	1148	3091	4761	2340	211	218	246	519	16749
2001	111	842	1247	360	2399	2777	3998	2520	307	105	114	151	14931
2002	155	197	231	198	682	4820	7586	4683	1433	155	217	434	20791
2003	287	247	653	877	1137	2175	2150	166	111	109	179	138	8229
2004	144	255	1326	1274	2226	2209	1677	163	150	135	131	178	9868
2005	191	154	165	171	248	2798	3106	1410	135	136	103	139	8756
2006	98	890	2002	1843	1254	4200	8712	4378	400	193	111	148	24229
2007	170	2186	1058	1357	884	3171	4675	1511	140	137	134	133	15556
2008	150	999	1143	755	1205	2612	3353	4290	296	133	120	166	15222
2009	128	352	289	681	334	1582	4356	839	108	116	102	106	8993
2010	136	161	158	166	1726	3989	5480	3779	261	184	161	429	16630
2011	259	1483	1972	2370	4252	8286	9255	5816	931	1286	1810	1075	38795
2012	321	538	1032	536	683	3915	2638	387	238	172	158	166	10784
Max	346	2186	2002	2370	4252	8286	10034	5816	2158	1286	1810	1075	38795
Min	98	119	95	85	92	254	351	106	88	72	102	80	3171
Mean	212	579	850	640	1001	2438	3679	1950	557	213	220	250	12588

Table E.7 Storage of Sirikit Dam

Year	Storage (MCM)												Wet (MCM)	Dry (MCM)
	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR		
1975	6,459	6,156	6,449	6,915	8,872	9,643	9,507	9,296	8,969	8,766	8,356	7,743	6,459	9,507
1976	6,970	6,304	5,820	5,772	6,560	7,658	8,178	8,080	7,737	7,373	6,897	6,252	6,970	8,178
1977	5,619	5,051	4,444	4,233	4,477	5,238	5,362	5,081	4,939	4,848	4,683	4,337	5,619	5,362
1978	3,959	3,790	3,825	4,500	6,080	7,415	7,833	7,783	7,523	7,210	6,743	5,947	3,959	7,833
1979	5,176	4,646	4,697	4,431	4,825	5,077	4,900	4,509	4,276	4,140	3,985	3,761	5,176	4,900
1980	3,505	3,300	3,476	4,336	5,309	7,428	7,603	7,596	7,449	7,148	6,678	6,117	3,505	7,603
1981	5,447	5,203	4,822	7,162	7,661	8,272	8,447	8,207	8,015	7,702	7,180	6,398	5,447	8,447
1982	5,651	5,150	5,073	5,278	5,673	6,910	7,596	7,488	7,318	6,938	6,427	5,789	5,651	7,596
1983	4,864	4,388	4,273	4,302	5,208	6,425	7,256	7,502	7,590	7,506	7,116	6,403	4,864	7,256
1984	5,729	5,427	5,514	6,378	7,254	8,159	8,533	8,260	8,207	7,847	7,241	6,322	5,729	8,533
1985	5,433	5,005	4,903	5,201	6,857	7,664	8,016	8,224	8,241	8,145	7,683	6,930	5,433	8,016
1986	6,328	6,079	5,782	6,117	6,565	7,053	6,993	6,511	6,378	6,111	5,463	4,847	6,328	6,993
1987	4,245	3,733	3,608	3,281	3,914	4,441	4,766	4,781	4,806	4,670	4,169	3,782	4,245	4,766
1988	3,606	3,750	4,012	4,664	5,990	6,425	6,676	6,648	6,652	6,494	6,201	5,876	3,606	6,676
1989	5,333	5,022	5,092	5,546	5,926	6,371	6,639	6,448	6,414	6,208	5,831	5,131	5,333	6,639
1990	4,507	4,238	4,203	4,504	4,958	5,394	5,449	5,320	5,228	5,085	4,598	3,946	4,507	5,449
1991	3,401	3,284	3,376	3,376	3,875	4,645	4,858	4,746	4,654	4,500	4,203	3,776	3,401	4,858
1992	3,330	3,043	2,997	3,275	3,929	4,596	4,979	4,927	4,845	4,770	4,502	4,141	3,330	4,979
1993	3,765	3,511	3,402	3,747	3,639	4,016	4,196	3,853	3,722	3,596	3,395	3,190	3,765	4,196
1994	3,096	3,186	3,549	4,392	7,543	8,882	9,327	9,108	8,925	8,646	8,068	7,263	3,096	9,327
1995	6,530	6,027	5,739	6,468	8,900	9,476	9,440	9,397	9,205	8,850	8,164	7,143	6,530	9,440
1996	6,318	5,683	5,308	5,528	6,367	7,184	7,692	7,611	7,504	7,220	6,674	5,917	6,318	7,692
1997	5,259	4,701	4,339	4,335	5,111	6,282	6,799	6,563	6,337	6,004	5,392	4,777	5,259	6,799
1998	4,229	3,974	3,871	4,201	4,507	5,594	5,657	5,477	5,308	4,985	4,578	4,081	4,229	5,657
1999	3,892	4,035	4,408	4,713	6,115	8,183	8,832	9,050	9,071	8,585	7,779	6,839	3,892	8,832
2000	6,136	6,069	6,189	7,073	7,772	9,053	9,389	9,317	8,940	8,284	7,465	6,826	6,136	9,389
2001	5,903	5,746	5,905	6,678	8,671	9,008	9,361	9,433	9,103	8,538	7,798	6,875	5,903	9,361
2002	5,957	5,729	5,977	6,104	7,141	8,743	9,121	9,136	9,086	8,560	7,883	7,159	5,957	9,121
2003	6,585	5,784	5,532	5,928	6,722	8,210	8,321	7,883	7,442	6,981	6,356	5,604	6,585	8,321
2004	4,936	4,686	5,161	5,973	7,361	9,190	9,335	8,900	8,222	7,488	6,727	5,858	4,936	9,335
2005	5,194	4,464	4,472	4,733	6,271	8,016	8,609	8,607	8,102	7,440	6,716	5,845	5,194	8,609
2006	5,113	5,175	5,150	5,634	7,706	8,962	9,458	9,397	8,795	7,992	7,286	6,524	5,113	9,458
2007	5,854	5,819	5,655	5,499	6,044	6,782	7,446	7,250	6,768	6,125	5,568	4,921	5,854	7,446
2008	4,248	4,032	4,356	5,357	7,082	7,921	8,301	8,314	7,793	7,094	6,416	5,574	4,248	8,301
2009	4,805	4,296	4,209	5,007	5,366	5,825	6,023	5,864	5,390	4,910	4,394	3,911	4,805	6,023
2010	3,587	3,425	3,233	3,585	5,725	7,405	7,784	7,786	7,440	6,604	5,741	5,060	3,587	7,784
2011	4,772	5,039	5,922	7,366	8,920	9,404	9,495	9,417	8,787	7,756	6,483	5,612	4,772	9,495
Mean	4,931	4,656	4,673	5,157	6,209	7,182	7,494	7,380	7,152	6,755	6,187	5,521	4,931	7,494
Max	6,585	6,079	6,189	7,366	8,920	9,476	9,495	9,433	9,205	8,850	8,164	7,263	6,585	9,495
Min	3,096	3,043	2,997	3,275	3,639	4,016	4,196	3,853	3,722	3,596	3,395	3,190	3,096	4,196
Stdev	1,024	942	921	1,142	1,451	1,590	1,631	1,676	1,608	1,480	1,351	1,188	1,024	1,631

Table E.8 Release of Sirikit Dam

Year	Release (MCM/month)												Annual (MCM)
	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	
1975	573	440	350	599	729	709	641	494	468	341	546	702	6,845
1976	826	815	814	626	623	476	449	443	531	534	546	714	7,284
1977	714	752	732	723	734	268	302	527	267	193	239	414	5,632
1978	478	259	302	311	206	286	293	276	376	410	490	856	4,859
1979	793	735	459	554	673	418	469	519	308	213	175	277	5,097
1980	297	309	188	192	138	287	305	206	258	376	472	626	4,074
1981	714	647	738	430	1,062	536	418	528	323	417	605	793	7,344
1982	849	587	265	471	656	200	215	340	262	457	551	680	5,680
1983	997	666	288	525	328	111	42	60	48	187	478	777	4,265
1984	756	489	264	345	602	709	228	518	165	457	665	972	6,396
1985	983	573	299	270	193	224	64	113	127	193	544	850	4,180
1986	729	679	682	556	397	303	422	667	233	319	687	658	6,237
1987	634	571	266	453	304	118	72	189	46	193	542	412	3,403
1988	237	140	64	147	120	180	141	172	77	209	340	357	2,502
1989	556	558	144	168	430	476	203	342	106	267	429	727	4,485
1990	636	480	375	411	412	432	321	330	169	209	507	655	4,887
1991	587	318	150	332	313	60	182	261	160	216	340	466	3,263
1992	465	320	119	119	25	57	39	208	210	149	292	411	2,367
1993	417	353	295	426	736	258	126	457	195	175	238	275	3,670
1994	137	103	30	15	101	302	160	447	342	369	629	824	4,067
1995	746	598	473	269	823	1,177	754	527	376	483	799	1,081	8,298
1996	939	794	738	646	734	359	213	374	244	383	615	775	6,595
1997	721	634	410	446	332	178	199	463	339	421	659	659	5,353
1998	614	331	226	157	335	50	183	320	234	376	449	546	3,483
1999	277	66	38	134	158	103	11	41	82	599	917	1,006	3,935
2000	778	452	371	273	334	128	281	332	527	765	895	807	6,134
2001	970	406	148	407	725	1,281	230	187	479	683	830	980	7,299
2002	943	740	380	629	474	43	217	286	244	683	787	847	5,968
2003	639	884	495	517	429	97	234	629	550	573	700	802	6,673
2004	763	440	167	406	187	373	339	667	831	876	839	949	6,819
2005	745	807	420	406	215	101	229	299	683	805	818	931	6,578
2006	865	374	288	223	264	255	413	300	789	939	814	850	6,249
2007	740	264	500	526	527	276	209	449	643	756	673	722	6,325
2008	779	489	427	483	349	276	249	330	719	855	790	940	6,785
2009	878	684	394	287	392	297	248	354	597	595	589	542	5,344
2010	366	251	329	266	132	60	111	181	512	926	928	770	5,127
2011	408	212	193	479	1,581	1,831	946	425	851	1,217	1,385	961	10,080
Max	997	884	814	723	1,581	1,831	946	667	851	1,217	1,385	1,081	10,080
Min	137	66	30	15	25	43	11	41	46	149	175	275	2,367
Mean	663	492	347	385	453	359	275	358	361	482	616	719	5,502

Table E.9 Storage of Bhumibol Dam

Year	Storage (MCM)												Wet (MC	Dry (MCM)
	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR		
1975	9,984	9,445	9,397	9,385	10,404	12,491	13,480	13,375	13,230	12,976	12,553	11,777	9,984	13,480
1976	10,952	10,388	9,525	8,577	8,591	9,274	10,500	10,916	10,792	10,714	10,248	9,442	10,95	10,500
1977	8,566	7,785	7,086	6,439	6,314	8,329	8,881	8,794	8,665	8,609	8,146	7,498	8,566	8,881
1978	6,816	6,465	5,966	6,706	7,847	9,276	10,589	10,701	10,574	10,236	9,736	8,851	6,816	10,589
1979	7,957	7,342	7,192	6,646	6,500	6,791	7,262	6,470	5,963	5,629	5,318	4,945	7,957	7,262
1980	4,616	4,683	4,946	5,111	5,598	7,540	9,100	9,427	9,558	9,353	8,935	8,228	4,616	9,100
1981	7,599	7,080	6,760	7,308	8,274	9,028	9,485	10,057	10,228	10,076	9,437	8,538	7,599	9,485
1982	7,997	7,662	7,778	7,290	7,182	8,435	9,448	9,588	9,539	9,216	8,527	7,515	7,997	9,448
1983	6,755	6,120	5,808	5,374	5,586	6,658	8,110	9,485	9,804	9,785	9,150	8,243	6,755	8,110
1984	7,439	6,935	7,023	6,894	6,942	7,663	8,912	9,077	9,140	8,895	8,368	7,603	7,439	8,912
1985	7,030	6,715	6,774	6,974	7,188	8,286	9,395	10,808	11,135	11,077	10,519	9,730	7,030	9,395
1986	9,048	8,779	8,435	8,229	8,555	9,240	9,349	9,003	8,954	8,730	8,119	7,115	9,048	9,349
1987	6,284	5,797	5,714	5,083	5,365	6,491	7,417	7,924	8,133	8,011	7,646	6,468	6,284	7,417
1988	5,457	5,545	6,235	6,629	7,346	8,157	9,934	10,611	10,796	10,506	9,712	8,371	5,457	9,934
1989	7,108	6,633	6,812	6,917	6,717	7,012	8,415	8,415	8,461	8,148	7,570	6,565	7,108	8,415
1990	5,667	5,332	5,191	5,070	5,131	5,724	6,337	6,404	6,268	5,926	5,545	4,884	5,667	6,337
1991	4,286	4,109	4,254	4,242	4,902	5,983	6,798	6,980	6,824	6,494	5,961	5,211	4,286	6,798
1992	4,494	3,996	3,902	3,951	4,529	5,776	6,935	7,136	7,149	7,036	6,584	5,953	4,494	6,935
1993	5,318	4,867	4,507	4,240	4,009	4,871	5,289	5,011	4,976	4,853	4,644	4,440	5,318	5,289
1994	4,324	4,404	4,822	5,490	7,427	9,709	10,481	10,486	10,458	10,285	9,809	8,991	4,324	10,481
1995	8,293	7,891	7,415	7,441	8,774	10,912	11,944	12,138	12,027	11,596	10,921	9,891	8,293	11,944
1996	8,998	8,466	8,252	8,157	8,552	10,152	11,132	11,377	11,250	10,732	9,870	8,839	8,998	11,132
1997	8,055	7,147	6,530	6,254	6,910	7,782	8,815	8,798	8,557	8,099	7,449	6,465	8,055	8,815
1998	5,485	4,994	4,752	4,734	4,801	5,449	5,511	5,353	5,232	4,956	4,604	4,341	5,485	5,511
1999	4,152	4,577	4,925	4,977	5,751	6,850	8,059	9,314	9,506	9,266	8,723	8,033	4,152	8,059
2000	7,719	8,095	8,625	9,013	9,283	10,184	11,083	11,467	11,319	10,853	10,179	9,717	7,719	11,083
2001	8,951	8,754	8,781	8,902	10,171	10,779	11,377	11,799	11,622	11,250	10,692	9,841	8,951	11,377
2002	9,115	8,907	8,873	8,859	9,576	12,500	13,300	13,412	13,238	12,859	12,147	11,230	9,115	13,300
2003	10,313	9,354	8,592	8,501	8,569	9,516	9,701	9,167	8,484	7,825	7,111	6,303	10,31	9,701
2004	5,577	5,567	6,065	6,163	6,761	8,033	8,384	8,110	7,878	7,431	7,001	6,516	5,577	8,384
2005	6,161	5,762	5,517	5,692	6,395	8,959	10,065	10,583	10,370	9,788	9,218	8,606	6,161	10,065
2006	8,130	8,371	8,590	9,040	10,006	12,621	13,291	13,245	12,545	11,710	10,785	9,696	8,130	13,291
2007	8,757	9,434	9,185	8,576	8,618	9,691	11,415	11,511	10,824	9,793	8,788	7,566	8,757	11,415
2008	6,368	6,565	6,511	6,351	6,795	7,684	9,085	9,974	9,460	8,477	7,481	6,497	6,368	9,085
2009	5,574	5,443	5,785	6,074	6,337	7,536	9,347	9,344	8,508	7,578	6,513	5,455	5,574	9,347
2010	4,766	4,321	4,060	4,014	5,040	6,482	8,494	8,774	8,281	7,445	6,560	6,169	4,766	8,494
2011	6,070	6,947	7,747	8,522	10,483	12,554	13,394	13,316	12,676	11,172	9,483	7,804	6,070	13,394
Max	10,952	10,388	9,525	9,385	10,483	12,621	13,480	13,412	13,238	12,976	12,553	11,777	10,95	13,480
Min	4,152	3,996	3,902	3,951	4,009	4,871	5,289	5,011	4,976	4,853	4,604	4,341	4,152	5,289
Mean	7,032	6,775	6,712	6,698	7,222	8,498	9,473	9,685	9,525	9,119	8,488	7,658	7,032	9,473

Table E.10 Release of Bhumibol Dam

Year	Release (MCM/month)												Annual (MCM)
	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	
1975	786	599	570	611	515	382	638	876	558	469	533	801	7,350
1976	796	750	942	1,005	514	307	307	347	397	402	502	758	7,142
1977	910	921	728	736	640	315	453	719	392	290	500	635	6,943
1978	615	473	528	421	339	270	230	264	366	383	466	804	5,366
1979	820	715	552	680	663	428	466	890	548	322	287	338	6,181
1980	292	236	165	169	127	46	37	115	159	275	449	659	3,202
1981	765	688	597	116	126	183	223	332	191	294	605	871	4,804
1982	579	537	493	779	770	235	143	266	233	401	700	978	6,209
1983	676	594	357	444	178	54	17	13	31	136	664	832	4,065
1984	745	512	192	303	451	204	44	213	109	280	504	685	4,024
1985	527	389	190	199	293	127	28	34	73	213	634	797	3,682
1986	704	518	539	516	335	234	486	613	213	297	593	926	6,077
1987	806	487	290	629	587	109	38	270	42	205	364	1,074	5,039
1988	944	225	60	124	21	21	17	15	118	421	812	1,253	4,227
1989	1,140	579	166	231	699	356	39	430	152	363	552	919	5,309
1990	824	572	416	314	368	410	317	385	305	372	351	571	4,863
1991	482	196	87	183	254	135	35	309	309	411	529	669	3,714
1992	600	418	103	84	22	48	35	137	323	241	450	602	3,018
1993	553	435	409	330	396	54	182	431	127	138	185	220	3,076
1994	168	150	75	38	46	81	195	413	339	307	516	848	3,699
1995	690	594	620	294	102	33	62	249	328	566	865	1,088	5,753
1996	952	730	664	525	636	539	249	471	350	648	908	1,112	7,700
1997	867	943	662	559	254	191	203	397	451	526	675	977	6,748
1998	910	474	224	105	185	32	64	216	146	253	282	219	2,360
1999	162	37	6	84	86	56	7	59	103	342	593	682	2,496
2000	442	281	86	77	333	196	54	110	318	529	652	535	3,844
2001	674	411	109	282	133	128	125	83	346	461	584	791	4,133
2002	680	541	255	322	208	44	285	953	736	722	861	993	6,836
2003	916	1,041	858	430	360	169	218	651	659	617	635	695	6,932
2004	599	332	147	357	184	168	228	455	326	447	410	467	3,908
2005	388	421	464	279	237	153	188	350	536	735	618	619	5,192
2006	592	369	325	306	354	136	937	460	927	959	975	1,041	7,642
2007	853	270	664	912	595	267	96	361	884	1,074	986	1,053	8,291
2008	1,130	331	321	396	251	210	169	156	714	992	920	952	6,306
2009	894	494	328	277	388	240	139	362	906	933	972	922	6,520
2010	559	376	257	186	87	56	55	142	595	806	806	505	4,557
2011	308	108	105	167	667	783	1,604	721	1,009	1,715	1,750	1,542	10,170
Max	1,140	1,041	942	1,005	770	783	1,604	953	1,009	1,715	1,750	1,542	10,170
Min	162	37	6	38	21	21	7	13	31	136	185	219	2,360
Mean	685	480	366	364	335	200	233	359	387	501	640	795	5,335

Table E.11 Raw water demand of PWA and MWA

PWA/ MWA	Head office/Service unit	Raw water demand (x1,000 Cu.m)							
		2005	2006	2007	2008	2009	2010	2011	2012
PWA01	Uttaradit head office	428	436	381	315	315	249	260	276
	Tron service unit	222	217	187	114	114	121	127	141
	Dan Na Kham service unit	316	360	392	297	297	394	412	406
	Total	967	1,013	960	726	726	764	799	823
PWA02	Phrom Phiram service unit	818	837	771	636	636	674	695	748
	Bang Krathum service unit	352	375	342	275	275	358	369	348
	Noen Kum service unit	241	257	231	121	121	143	147	157
	Ban Mai service unit	301	299	258	157	157	143	147	140
	Hao Lor service unit	1,393	1,525	1,564	1,586	1,586	1,612	1,662	2,926
	Total	3,105	3,292	3,167	2,775	2,775	2,929	3,019	4,319
PWA03	Phitchit head office	5,147	5,359	4,875	3,584	3,584	3,693	3,821	4,087
	Sak Lek service unit	367	460	419	319	319	371	384	437
	Wang Srai Phoon service unit	280	393	360	200	200	241	250	261
	Tha Ror service unit	369	284	255	176	176	176	182	188
	Wang Khud service unit	321	482	436	321	321	345	357	368
	Hao Dong service unit	386	340	340	208	208	214	221	264
	Kok Salud service unit	412	462	512	356	356	443	458	483
	Total	7,282	7,781	7,198	5,164	5,164	5,483	5,673	6,086
PWA04	Bang Mun Nak head office	2,063	2,128	1,899	1,280	1,280	1,223	1,226	1,368
	Bang Pai service unit	174	177	155	91	91	87	87	99
	Tapan Hin head office	2,977	3,050	2,734	1,903	1,903	1,961	1,983	2,022
	Tup Kor service unit	1,185	1,237	1,142	778	778	815	824	894
	Total	6,400	6,593	5,930	4,052	4,052	4,086	4,120	4,382
PWA05	Ta Krit service unit	571	602	548	354	354	348	365	501
	Total	571	602	548	354	354	348	365	501
PWA06	Nakon Sawan head office	2,602	2,833	2,626	1,975	1,975	2,296	2,408	2,606
	Phayuhakiri head office	2,819	2,944	2,699	2,102	2,102	2,143	2,201	2,480
	Kao Thong service unit	802	869	793	561	561	647	665	773
	Chainat head office	3,025	3,154	2,884	2,434	2,434	2,397	2,465	2,976
	Total	9,248	9,800	9,002	7,072	7,072	7,483	7,738	8,836
PWA07	Angthong head office	3,250	3,425	3,089	2,918	2,918	2,795	2,844	3,308
	Pathumthani head office	15,770	18,392	20,351	24,619	24,619	22,551	23,780	29,745
	Rangsit head office	73,615	82,692	108,945	120,688	120,688	121,996	128,994	145,450
	Singburi head office	3,606	3,645	3,271	2,803	2,803	2,821	2,844	2,940
	Sena head office	2,510	2,623	2,413	2,649	2,649	2,606	2,696	2,955
	Phranakornsri Ayutthaya head office	9,883	12,365	26,848	32,158	32,158	31,146	33,332	38,193
	Total	108,634	123,142	164,917	185,834	185,834	183,914	194,490	222,592
Total PWA		136,207	152,223	191,721	205,978	205,978	205,008	216,204	247,538
MWA		1,131,000	1,173,000	1,224,000	1,250,600	1,250,300	1,281,900	1,302,300	1,367,615
	Total	1,131,000	1,173,000	1,224,000	1,250,600	1,250,300	1,281,900	1,302,300	1,367,615
Total MWA		1,131,000	1,173,000	1,224,000	1,250,600	1,250,300	1,281,900	1,302,300	1,367,615

Table E.12 Raw water demand of PWA and MWA by sector

Head office/Service unit	Sector	Raw water demand (MCM)							
		2005	2006	2007	2008	2009	2010	2011	2012
Uttaradit head office	Domestic	0.63	0.66	0.63	0.48	0.48	0.50	0.52	0.54
	Business	0.28	0.29	0.28	0.21	0.21	0.22	0.23	0.24
	Industrial	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04
Total		0.97	1.01	0.96	0.73	0.73	0.76	0.80	0.82
Phitsanulok	Domestic	1.90	2.01	1.94	1.70	1.70	1.79	1.85	2.64
	Business	1.04	1.10	1.06	0.93	0.93	0.98	1.01	1.45
	Industrial	0.16	0.17	0.17	0.15	0.15	0.16	0.16	0.23
Total		3.11	3.29	3.17	2.78	2.78	2.93	3.02	4.32
Phitchit	Domestic	4.63	4.94	4.57	3.28	3.28	3.48	3.60	3.87
	Business	1.83	1.95	1.80	1.29	1.29	1.37	1.42	1.53
	Industrial	0.83	0.89	0.82	0.59	0.59	0.62	0.65	0.69
Total		7.28	7.78	7.20	5.16	5.16	5.48	5.67	6.09
Bang Mun Nak head office	Domestic	1.25	1.28	1.14	0.76	0.76	0.73	0.73	0.82
	Business	0.77	0.79	0.71	0.47	0.47	0.45	0.45	0.51
	Industrial	0.22	0.23	0.20	0.13	0.13	0.13	0.13	0.14
Total		2.24	2.31	2.05	1.37	1.37	1.31	1.31	1.47
Tapan Hin head office	Domestic	2.69	2.77	2.50	1.73	1.73	1.79	1.81	1.88
	Business	1.19	1.22	1.10	0.76	0.76	0.79	0.80	0.83
	Industrial	0.29	0.30	0.27	0.19	0.19	0.19	0.20	0.20
Total		4.16	4.29	3.88	2.68	2.68	2.78	2.81	2.92
Ta Krit service unit	Domestic	0.40	0.42	0.38	0.25	0.25	0.24	0.25	0.35
	Business	0.12	0.13	0.12	0.08	0.08	0.07	0.08	0.11
	Industrial	0.05	0.06	0.05	0.03	0.03	0.03	0.03	0.05
Total		0.57	0.60	0.55	0.35	0.35	0.35	0.37	0.50
Nakon Sawan head office	Domestic	1.81	1.97	1.82	1.37	1.37	1.59	1.67	1.81
	Business	0.55	0.60	0.56	0.42	0.42	0.49	0.51	0.56
	Industrial	0.24	0.26	0.24	0.18	0.18	0.21	0.22	0.24
Total		2.60	2.83	2.63	1.98	1.98	2.30	2.41	2.61
Phayuhakiri head office	Domestic	2.07	2.18	1.99	1.52	1.52	1.59	1.64	1.86
	Business	0.76	0.80	0.74	0.56	0.56	0.59	0.60	0.69
	Industrial	0.79	0.83	0.76	0.58	0.58	0.61	0.62	0.71
Total		3.62	3.81	3.49	2.66	2.66	2.79	2.87	3.25
Chainat head office	Domestic	1.65	1.72	1.57	1.33	1.33	1.31	1.35	1.62
	Business	1.03	1.07	0.98	0.83	0.83	0.81	0.84	1.01
	Industrial	0.35	0.36	0.33	0.28	0.28	0.28	0.28	0.34
Total		3.02	3.15	2.88	2.43	2.43	2.40	2.46	2.98

Table E.12 Raw water demand of PWA and MWA by sector (continue)

Head office/Service unit	Type	Raw water demand (MCM)							
		2005	2006	2007	2008	2009	2010	2011	2012
Angthong head office	Domestic	1.97	2.08	1.88	1.77	1.77	1.70	1.73	2.01
	Business	0.98	1.03	0.93	0.88	0.88	0.84	0.86	1.00
	Industrial	0.30	0.31	0.28	0.27	0.27	0.25	0.26	0.30
Total		3.25	3.42	3.09	2.92	2.92	2.80	2.84	3.31
Pathumthani head office	Domestic	6.27	7.31	8.09	9.78	9.78	8.96	9.45	11.82
	Business	2.60	3.04	3.36	4.06	4.06	3.72	3.93	4.91
	Industrial	6.90	8.05	8.91	10.77	10.77	9.87	10.41	13.02
Total		15.77	18.39	20.35	24.62	24.62	22.55	23.78	29.75
Rangsit head office	Domestic	26.38	29.63	39.04	43.25	43.25	43.71	46.22	52.12
	Business	20.25	22.74	29.97	33.20	33.20	33.55	35.48	40.01
	Industrial	26.99	30.32	39.94	44.25	44.25	44.73	47.29	53.33
Total		73.61	82.69	108.95	120.69	120.69	122.00	128.99	145.45
Singburi head office	Domestic	2.07	2.09	1.87	1.61	1.61	1.62	1.63	1.68
	Business	1.28	1.29	1.16	0.99	0.99	1.00	1.01	1.04
	Industrial	0.26	0.26	0.24	0.20	0.20	0.20	0.21	0.21
Total		3.61	3.64	3.27	2.80	2.80	2.82	2.84	2.94
Sena head office	Domestic	1.54	1.61	1.48	1.63	1.63	1.60	1.65	1.81
	Business	0.75	0.79	0.72	0.79	0.79	0.78	0.81	0.88
	Industrial	0.22	0.23	0.21	0.23	0.23	0.23	0.23	0.26
Total		2.51	2.62	2.41	2.65	2.65	2.61	2.70	2.95
Phranakornsri Ayutthaya head office	Domestic	2.82	3.53	7.67	9.18	9.18	8.89	9.52	10.91
	Business	3.36	4.21	9.14	10.95	10.95	10.60	11.35	13.00
	Industrial	3.70	4.63	10.04	12.03	12.03	11.65	12.47	14.29
Total		9.88	12.37	26.85	32.16	32.16	31.15	33.33	38.19
MWA	Domestic	532.2	540.1	571	586	615	629.7	625.2	642.32
	Business+Industrial	598.8	632.9	653	664.6	635.3	652.2	677.1	725.295
Total		1131	1173	1224	1250.6	1250.3	1281.9	1302.3	1367.615

Table E.13 Forecasting raw water demand of PWA and MWA by sector

Head office/Service unit	Type	Raw water demand (MCM)												
		2012	2014	2019	2024	2029	2034	2039	2075	2079	2084	2089	2094	2099
Uttaradit head office	Domestic	0.51	0.56	0.66	0.77	0.91	1.02	1.13	1.96	2.05	2.16	2.28	2.39	2.51
	Business	0.23	0.25	0.30	0.34	0.41	0.45	0.50	0.87	0.91	0.96	1.01	1.06	1.11
	Industrial	0.04	0.05	0.05	0.06	0.07	0.08	0.09	0.16	0.17	0.18	0.19	0.20	0.20
Total		0.78	0.85	1.01	1.18	1.39	1.55	1.72	2.98	3.12	3.30	3.47	3.65	3.82
Phitsanulok	Domestic	1.83	1.95	2.27	2.59	3.01	3.30	3.63	6.05	6.31	6.65	6.98	7.32	7.65
	Business	1.00	1.07	1.24	1.42	1.65	1.81	1.99	3.31	3.46	3.64	3.83	4.01	4.20
	Industrial	0.16	0.17	0.20	0.22	0.26	0.29	0.31	0.52	0.55	0.58	0.61	0.63	0.66
Total		2.99	3.20	3.71	4.23	4.91	5.39	5.94	9.88	10.32	10.87	11.42	11.97	12.51
Phitchit	Domestic	3.31	3.42	3.54	3.69	3.98	4.14	4.33	5.73	5.89	6.08	6.28	6.47	6.67
	Business	1.30	1.35	1.40	1.45	1.57	1.63	1.71	2.26	2.32	2.40	2.48	2.55	2.63
	Industrial	0.59	0.61	0.63	0.66	0.71	0.74	0.78	1.03	1.06	1.09	1.13	1.16	1.19
Total		5.20	5.38	5.57	5.80	6.26	6.51	6.81	9.02	9.27	9.57	9.88	10.19	10.49
Bang Mun Nak head office	Domestic	0.67	0.68	0.70	0.73	0.79	0.81	0.84	1.06	1.09	1.12	1.15	1.18	1.21
	Business	0.42	0.42	0.44	0.45	0.49	0.50	0.52	0.66	0.67	0.69	0.71	0.73	0.75
	Industrial	0.12	0.12	0.12	0.13	0.14	0.14	0.15	0.19	0.19	0.20	0.20	0.21	0.21
Total		1.21	1.22	1.26	1.32	1.42	1.45	1.51	1.91	1.95	2.00	2.06	2.12	2.17
Tapan Hin head office	Domestic	1.74	1.79	1.94	2.11	2.36	2.49	2.66	3.89	4.03	4.20	4.37	4.54	4.72
	Business	0.77	0.79	0.86	0.93	1.04	1.10	1.17	1.72	1.78	1.86	1.93	2.01	2.08
	Industrial	0.19	0.19	0.21	0.23	0.26	0.27	0.29	0.42	0.44	0.46	0.47	0.49	0.51
Total		2.69	2.78	3.01	3.27	3.65	3.85	4.12	6.03	6.25	6.51	6.78	7.04	7.31
Ta Krit service unit	Domestic	0.26	0.28	0.34	0.39	0.46	0.51	0.57	0.98	1.03	1.08	1.14	1.20	1.26
	Business	0.08	0.09	0.10	0.12	0.14	0.16	0.17	0.30	0.32	0.33	0.35	0.37	0.39
	Industrial	0.04	0.04	0.05	0.05	0.06	0.07	0.08	0.13	0.14	0.15	0.15	0.16	0.17
Total		0.38	0.41	0.49	0.57	0.66	0.74	0.82	1.41	1.48	1.56	1.64	1.73	1.81
Nakon Sawan head office	Domestic	1.70	1.84	2.19	2.54	2.99	3.32	3.69	6.36	6.66	7.03	7.40	7.77	8.14
	Business	0.52	0.57	0.67	0.78	0.92	1.02	1.13	1.95	2.05	2.16	2.27	2.39	2.50
	Industrial	0.23	0.25	0.29	0.34	0.40	0.45	0.50	0.85	0.89	0.94	0.99	1.04	1.09
Total		2.45	2.65	3.16	3.66	4.31	4.79	5.32	9.17	9.60	10.13	10.66	11.20	11.73
Phayuhakiri head office	Domestic	1.44	1.51	1.72	1.92	2.21	2.39	2.61	4.17	4.35	4.57	4.78	5.00	5.22
	Business	0.53	0.56	0.63	0.71	0.82	0.88	0.96	1.54	1.61	1.69	1.77	1.85	1.93
	Industrial	0.55	0.58	0.66	0.73	0.84	0.91	1.00	1.59	1.66	1.74	1.83	1.91	1.99
Total		2.52	2.65	3.00	3.37	3.86	4.18	4.57	7.31	7.62	8.00	8.38	8.76	9.14
Chainat head office	Domestic	1.27	1.34	1.53	1.73	1.99	2.16	2.37	3.84	4.01	4.21	4.42	4.62	4.83
	Business	0.79	0.83	0.95	1.07	1.24	1.35	1.47	2.39	2.49	2.62	2.74	2.87	3.00
	Industrial	0.27	0.28	0.32	0.36	0.42	0.46	0.50	0.81	0.84	0.89	0.93	0.97	1.02
Total		2.32	2.46	2.81	3.17	3.64	3.97	4.34	7.04	7.34	7.72	8.09	8.47	8.84

Table E.13 Forecasting raw water demand of PWA and MWA by sector (continue)

Head office/Service unit	Sector	Raw water demand (MCM)												
		2012	2014	2019	2024	2029	2034	2039	2075	2079	2084	2089	2094	2099
Angthong head office	Domestic	1.59	1.65	1.82	2.01	2.26	2.41	2.60	3.96	4.11	4.30	4.48	4.67	4.86
	Business	0.79	0.82	0.91	1.00	1.12	1.20	1.29	1.97	2.04	2.14	2.23	2.32	2.42
	Industrial	0.24	0.25	0.27	0.30	0.34	0.36	0.39	0.59	0.62	0.65	0.67	0.70	0.73
Total		2.62	2.73	3.01	3.30	3.73	3.98	4.29	6.52	6.77	7.08	7.39	7.70	8.01
Pathumthani head office	Domestic	10.56	11.67	14.39	17.12	20.49	23.10	25.96	46.57	48.86	51.72	54.58	57.44	60.30
	Business	4.39	4.85	5.98	7.11	8.51	9.60	10.79	19.35	20.30	21.49	22.68	23.87	25.05
	Industrial	11.63	12.86	15.85	18.85	22.57	25.44	28.60	51.29	53.81	56.97	60.12	63.27	66.42
Total		26.59	29.38	36.23	43.08	51.56	58.14	65.34	117.21	122.9	130.1	137.3	144.5	151.7
Rangsit head office	Domestic	48.56	53.82	66.69	79.56	95.43	107.80	121.33	218.69	229.5	243.0	256.5	270.0	283.5
	Business	37.28	41.31	51.19	61.07	73.25	82.75	93.13	167.86	176.1	186.5	196.9	207.3	217.6
	Industrial	49.69	55.06	68.24	81.40	97.64	110.30	124.13	223.75	234.8	248.6	262.4	276.3	290.1
Total		135.5	150.1	186.1	222.0	266.3	300.85	338.59	610.30	640.4	678.2	715.9	753.7	791.4
Singburi head office	Domestic	1.36	1.38	1.44	1.51	1.64	1.68	1.76	2.29	2.35	2.43	2.50	2.58	2.65
	Business	0.84	0.85	0.89	0.94	1.02	1.04	1.09	1.42	1.46	1.50	1.55	1.59	1.64
	Industrial	0.17	0.17	0.18	0.19	0.21	0.21	0.22	0.29	0.30	0.31	0.32	0.32	0.33
Total		2.38	2.41	2.51	2.64	2.86	2.94	3.07	4.00	4.11	4.24	4.37	4.49	4.62
Sena head office	Domestic	1.54	1.63	1.87	2.12	2.46	2.68	2.94	4.83	5.04	5.30	5.56	5.82	6.08
	Business	0.75	0.80	0.91	1.04	1.20	1.31	1.44	2.35	2.46	2.58	2.71	2.84	2.97
	Industrial	0.22	0.23	0.27	0.30	0.35	0.38	0.42	0.69	0.71	0.75	0.79	0.83	0.86
Total		2.50	2.66	3.06	3.46	4.00	4.37	4.80	7.87	8.21	8.63	9.06	9.49	9.91
Phranakornsri Ayutthaya head office	Domestic	10.51	11.87	15.16	18.44	22.41	25.60	29.05	53.85	56.61	60.05	63.50	66.94	70.38
	Business	12.53	14.15	18.08	21.98	26.71	30.53	34.63	64.20	67.49	71.59	75.70	79.81	83.91
	Industrial	13.77	15.55	19.86	24.15	29.35	33.54	38.05	70.54	74.15	78.66	83.18	87.69	92.20
Total		36.80	41.56	53.11	64.58	78.47	89.67	101.73	188.59	198.2	210.3	222.3	234.4	246.5
MWA	Domestic	642	670	740	811	881	951	1,021	1,526	1,582	1,652	1,722	1,792	1,862
	Business+ Industrial	725	770	881	993	1,104	1,215	1,327	2,128	2,217	2,329	2,440	2,551	2,663
Total		1,368	1,440	1,622	1,803	1,985	2,166	2,348	3,654	3,799	3,981	4,162	4,344	4,525

Appendix F

Water network balance model

Appendix F

Water network balance model

F.1 Water network balance model

The water balance of water resources were considered at the control points though the main Nan River Basin. The balancing water volume will be separated into 2 terms such as the net flow volume at the control point for studying the flood issue and the water deficit for studying the water shortage issue.

F.1.1 Net flow volume

The net flow volume was analyzed by balancing the inflow (Q_{in}) and outflow (Q_{out}) of the control point. The lateral flow or side flow (Q_s) is one of variables that will be taken to the water balance equation. Another variable is the water extraction or water allocation (W_a) , the water allocation was extracted from the water resources system by the directly pumping and the irrigated infrastructure such the sluice gate and the weir. The net flow volume is following this equation as:

$$\Sigma Q_{out} = \Sigma Q_{in} \quad (1)$$

$$Q_{out} = Q_{in} + Q_s - W_a \quad (2)$$

where Q_{out} is the outflow of the runoff volume, MCM/month, Q_{in} is the inflow of the runoff volume, MCM/month, W_a is the water allocation or water extraction, MCM/month.

F.1.2 Water deficit

The water deficit was analyzed by balancing between the water allocation and the water demand. The assumption is the water deficit will occur while the water allocation less than the water demand. On the other hand, the deficit will not occur if the water allocation is higher than the water demand that will occur the residual water, this residual water calls the water surplus. The water surplus was assumed as the stilling water in the irrigation area that it will be not taken back to the water balance system. The water deficit is following this equation as:

$$D_t = W_{at} - W_{dt} \tag{3}$$

where D_t is the water deficit, MCM, W_{at} is the water allocation, MCM, W_{dt} is the irrigation water demand, MCM.

The water balance of river basin was analyzed the water resources system of Nan River Basin and Ping River. The Phisanulok Irrigation Project is the main water user in this Nan River Basin and the other irrigation projects included medium, small and pumping projects. Furthermore the Great Chao Phraya Irrigation Project receives the allocated water from both Bhumibol and Sirikit Dam at the Lower Chao Phraya River Basin.The lateral flow of sub basins at the downstream were assigned as the inflow to the flow network. The control points were created for water balancing between the upper node and lower node. The control points were set from the 7 runoff stations show as Figure F.1. Moreover the Lower Nan River Basin receive the lateral flow from the Lower Yom River Basin, so Y.17 at Ban Sam Ngam was set as lateral flow from Yom River Basin. The lateral flow of each sub basins were simulated by using HEC-HMS same as the inflow. For the lateral flow included the lateral flow from Lower Ping River Basin and the lateral flow from Wang River Basin. The control points of Ping River Basin were set from W.4A at Ban Wang Man and P.17 at Ban Tha Ngiu. The minimum flow was set as minimum water requirement at C.2.

The lateral flows or side flows (SF) were grouped from the bias simulated runoff in each sub basin according to the flow network from HEC-HMS rainfall-runoff model (as shown in Figure F.1). The side flows in can be grouped as:

1) SF-01 is the lateral flow from Nam Pad (0912).
2) SF-02 is the lateral flow from Nan River Part 4/1 (0911/1) and Klong Tron (0913).
3) SF-03 is the lateral flow from Nan River Part 4/2 (0911/2).
4) SF-04 is the lateral flow from Kwae Noi River Part 1 (0914/1), Kwae Noi River Part 2 (0914/2), Kwae Noi River Part 3

(0914/3), Kwae Noi River Part 4 (0914/4) and Nam Phak (0915).

5) SF-05 is the lateral flow from Wang Thong River (0916).
6) SF-06 is the lateral flow from Lower Nan River Part 1(0917/1), Lower Nan River Part 2 (0917/2) and Lower Nan River Part 3 (0917/3).
7) SF-07 is the lateral flow from Lower Nan River Part 4 (0917/4).

The water extraction (W_S) or water supply or pumping of the irrigation project along main Nan River is calibrated from the water balance in the past (1979 – 2006). The water extraction for simulating in the reservoir operation model can be calculated from the water allocation ratio (r_a) multiple with the net flow at the extraction point. The water allocation patterns are formulated from the ratio of water allocation and net flow at the extraction point with decision tree classification as shown in Table F.1 to F.6.

The water allocation ratio (r_a) at the each point can be calculated as follows:

1) Water allocation ratio (r_a) of Phitsanulok Irrigation Project (PSK)

$$r_{a\_psk} = \frac{W_{s\_psk}}{Q_{N.60}+S_{F\_03}} \qquad (4)$$

where W_{s_psk} is the water extraction of Phitsanulok Irrigation Project, $Q_{N.60}$ is the stream flow at N.60 and S_{F_03} is the lateral flow (SF-03).

2) Water allocation ratio (r_a) of WD-01

$$r_{a\_01} = \frac{W_{s\_01}}{Q_{N.60}+S_{F_{03}}-Ws\_psk} \qquad (5)$$

where W_{s_01} is the water extraction of WD-01, $Q_{N.60}$ is the stream flow at N.60A and S_{F_03} is the lateral flow (SF-03) , W_{s_psk} is the water extraction of Phitsanulok Irrigation Project.

3) Water allocation ratio (r_a) of WD-02

$$r_{a\_02} = \frac{W_{s\_02}}{Q_{N.27A}+S_{F\_04}} \qquad (5)$$

where W_{s_02} is the water extraction of WD-02, $Q_{N.27A}$ is the stream flow at N.27A and S_{F_04} is the lateral flow (SF-04).

4) Water allocation ratio (r_a) of WD-03

$$r_{a\_03} = \frac{W_{S\_03}}{Q_{N.5A}+S_{F\_05}} \tag{6}$$

where W_{s_03} is the water extraction of WD-03, $Q_{N.5A}$ is the stream flow at N.5A and S_{F_05} is the lateral flow (SF-05).

5) Water allocation ratio (r_a) of WD-04

$$r_{a\_04} = \frac{W_{S\_04}}{Q_{N.7A}+Q_{Y.17}+S_{F\_06}} \tag{7}$$

where W_{s_04} is the water extraction of WD-04, $Q_{N.7A}$ is the stream flow at N.7A, $Q_{Y.17}$ is the stream flow at Y.17 and S_{F_06} is the lateral flow (SF-06).

6) Water allocation ratio (r_a) of WD-05

$$r_{a\_05} = \frac{W_{S\_05}}{Q_{N.67}+Q_{P.17}+S_{F\_07}} \tag{8}$$

where W_{s_05} is the water extraction of WD-05, $Q_{N.67}$ is the stream flow at N.67, $Q_{Y.17}$ is the stream flow at P.17 and S_{F_07} is the lateral flow (SF-07).

7) Water allocation ratio (r_a) of Chao Phraya Irrigation Project

$$r_{a\_Nan} = \frac{W_{s\_chy}}{Q_{C.2}+Q_{sk}+Q_{up\_chy}} \tag{9}$$

where $Q_{C.2}$ is the stream flow at C.2, Q_{sk} is the lateral flow from Sakaekang River basin. W_{s_chy} is the water allocation of Chao Phraya Irrigation and Q_{up_chy} is the lateral flow from Upper Chao Phraya River Basin.

From the flow network, the equation of net flow in each control point can be derived as:

1) Control point N.12A :

$$Q_{N.12A} = O_{SK} + S_{F\_01} \tag{10}$$

where O_{SK} is the release of Sirikit Dam and S_{F_01} is the lateral flow from Nam Pad (0912).

2) Control point N.60 :

$$Q_{N.60} = Q_{N.12A} + S_{F\_02} - PWA01 \tag*{11)}$$

where S_{F_02} is the lateral flow from Nan River Part 4/1 (0911/1), Klong Tron (0913), and PWA01 is the pumping for waterworks 01.

3) Control point N.27A :

$$Q_{N.27A} = Q_{N.60} + S_{F\_03} - W_{s\_psk} - W_{s\_01} \tag{12}$$

$$W_{s\_psk} = r_{a\_psk}\, x\ (Q_{N.60} + S_{F\_03}) \tag{13}$$

$$W_{s\_01} = r_{a\_01}\, x\ (Q_{N.60} + S_{F\_03} - W_{s\_psk}) \tag{14}$$

where S_{F_03} is the lateral flow from Nan River Part 4/2 (0911/2), W_{s_psk} is the water extraction of Phitsanulok Irrigation Project W_{s_01} is the water extraction of WD-01, and r_{a_psk} is the water allocation ratio of Phitsanulok Irrigation Project and r_{a_01} is the water allocation ratio of WD-01.

4) Control point N.5A :

$$Q_{N.5A} = Q_{N.27A} + S_{F\_04} - W_{S\_02} - PWA02 \tag{15}$$

$$W_{s\_02} = r_{a\_02}\, x\ (Q_{N.27A} + S_{F\_04}) \tag{16}$$

where S_{F_04} is the lateral flow from Kwae Noi River Part 1 (0914/1), Kwae Noi River Part 2 (0914/2), Kwae Noi River Part 3 (0914/3), Kwae Noi River Part 4 (0914/4) and Nam Phak (0915), W_{s_02} is the water extraction of WD-02 and r_{a_02} is the water allocation ratio of WD-02, PWA02 is the pumping for waterworks 02.

5) Control point N.7A :

$$Q_{N.7A} = Q_{N.5A} + S_{F\_05} - W_{S\_03} - PWA03 \tag{17}$$

$$W_{s\_03} = r_{a\_03}\, x\ (Q_{N.5A} + S_{F\_05}) \tag{18}$$

where S_{F_05} is the lateral flow from Wang Thong River (0916), W_{s_03} is the water extraction of WD-03 and r_{a_03} is the water allocation ratio of WD-03, and PWA03 is the pumping for waterworks 03.

6) Control point N.67 :

$$Q_{N.67} = Q_{N.7A} + Q_{Y.17} + S_{F\_06} - W_{S\_03} - PWA04 - PWA05 \tag{19}$$

$$W_{s\_04} = r_{a\_04} x\ (Q_{N.7A} + Q_{Y.17} + S_{F\_06}) \tag{20}$$

where S_{F_06} is the lateral flow from Lower Nan River Part 1(0917/1), Lower Nan River Part 2 (0917/2) and Lower Nan River Part 3 (0917/3), W_{s_04} is the water extraction of WD-04 and r_{a_04} is the water allocation ratio of WD-04, and PWA04 and PWA05 the pumping for waterworks 04 and 05.

7) Control point C.2 :

$$Q_{C.2} = Q_{N.67} + Q_{P.17} + S_{F\_07} - W_{S\_04} - PWA06 \tag{21}$$

$$Q_{P.17} = O_{BP} + Q_{W.4A} + S_{F\_LP} - Loss \tag{22}$$

$$W_{s\_04} = r_{a\_04}\ x\ (Q_{N.67} + Q_{Y.17} + S_{F\_07}) \tag{23}$$

where S_{F_07} is the lateral flow from Lower Nan River Part 4 (0917/4), W_{s_04} is the water extraction of WD-04, O_{BP} is the release from Bhumibol Dam, $Q_{W.4A}$ is the stream flow at W.4A, S_{F_LP} is the lateral flow of Lower Ping River Basin, $Loss$ is the water loss in Lower Ping River Basin and r_{a_04} is the water allocation ratio of WD-04, and PWA06 is the pumping for waterworks 06.

8) Water deficit of the Phitsanulok Irrigation Project (PSK) :

$$D_{PSK} = W_{s\_psk} - W_{d\_psk} \tag{24}$$

where W_{s_psk} and W_{d_psk} is the water extraction of Phitsanulok Irrigation Project, respectively.

9) Water deficit of the Chao Phraya Irrigation Project (CHY) can be considered from the water supply of Nan and Ping River Basin and the water demand of Chao Phraya Irrigation Project as follows.

$$D_{Chy} = W_{s\_chy} - W_{d\_chy} \tag{25}$$

$$W_{s\_chy} = r_{a\_chy}\ x\ (Q_{C.2} + Q_{up\_chy} + Q_{sk} - PWA07 - MWA - Q_{eco}) \tag{26}$$

where D_{chy} is the total water deficit of Chao Phraya Irrigation Project. W_{s_chy} and W_{d_chy} is the water extraction of Chao Phraya Irrigation Project, respectively. r_{a_Chy} is the water allocation ratio for Chao Phraya Irrigation Project, $Q_{C.2}$ is the stream flow at C.2, Q_{up_chy} is the lateral flow from Upper Chao Phraya River Basin, Q_{eco} is the flow for ecosystem, PWA07 is the pumping for waterworks 07, and MWA is the pumping of MWA.

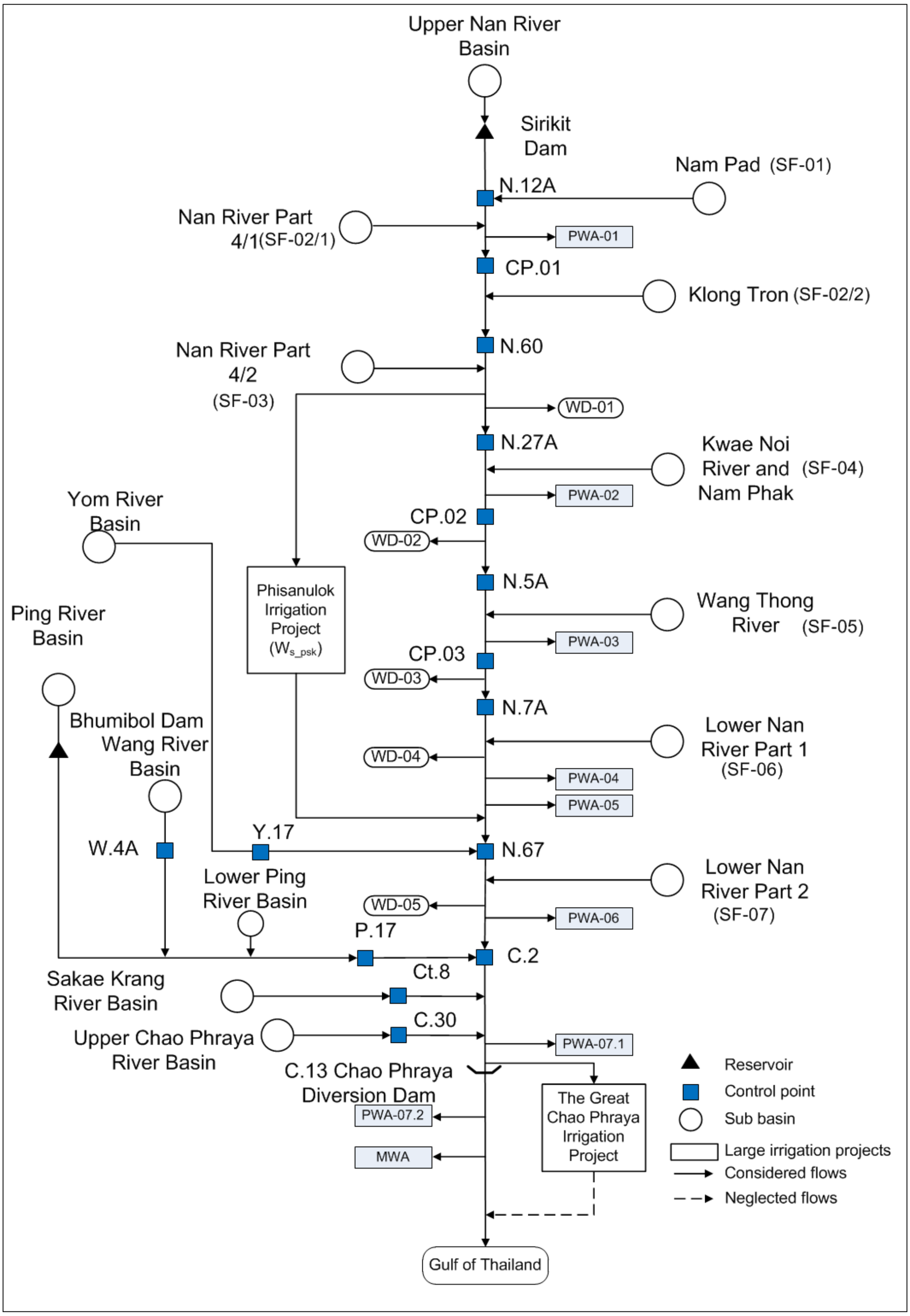


Figure F.1 The flow network of water resources system of Nan River Basin

Table F.1 The water allocation ratio of Phitsanulok Irrigation Project

Water season	Monthly level	Allocation ratio											
		May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
High	higher	0.16	0.02	0.04	0.09	0.02	0.01	0.13	0.07	0.24	0.19	0.15	0.16
	high	0.16	0.02	0.04	0.09	0.02	0.15	0.30	0.12	0.16	0.19	0.15	0.16
	medium	0.16	0.02	0.04	0.09	0.10	0.18	0.30	0.12	0.16	0.16	0.15	0.16
	low	0.17	0.02	0.11	0.15	0.04	0.18	0.30	0.12	0.16	0.16	0.15	0.15
	lower	0.17	0.02	0.08	0.36	0.04	0.18	0.30	0.12	0.16	0.16	0.15	0.15
Normal	higher	0.16	0.02	0.12	0.08	0.12	0.13	0.14	0.02	0.25	0.21	0.15	0.15
	high	0.16	0.02	0.12	0.08	0.10	0.21	0.13	0.05	0.20	0.21	0.15	0.15
	medium	0.16	0.02	0.12	0.17	0.16	0.24	0.32	0.04	0.22	0.21	0.16	0.15
	low	0.15	0.02	0.10	0.21	0.11	0.43	0.32	0.04	0.22	0.21	0.16	0.14
	lower	0.15	0.02	0.13	0.17	0.33	0.43	0.32	0.04	0.22	0.21	0.16	0.14
Dry	higher	0.21	0.03	0.20	0.23	0.26	0.03	0.26	0.05	0.32	0.24	0.10	0.12
	high	0.21	0.03	0.20	0.23	0.26	0.25	0.26	0.05	0.32	0.24	0.10	0.12
	medium	0.21	0.03	0.20	0.23	0.22	0.44	0.24	0.04	0.17	0.14	0.10	0.12
	low	0.12	0.02	0.13	0.16	0.20	0.44	0.24	0.04	0.17	0.14	0.10	0.10
	lower	0.12	0.01	0.09	0.16	0.20	0.44	0.24	0.04	0.17	0.14	0.10	0.10
Very Dry	higher	0.12	0.02	0.04	0.13	0.03	0.34	0.29	0.01	0.11	0.14	0.13	0.19
	high	0.12	0.02	0.04	0.13	0.03	0.43	0.29	0.01	0.11	0.14	0.13	0.19
	medium	0.12	0.02	0.04	0.13	0.03	0.43	0.29	0.01	0.11	0.14	0.13	0.19
	low	0.12	0.02	0.04	0.13	0.26	0.43	0.29	0.06	0.04	0.04	0.03	0.19
	lower	0.03	0.01	0.03	0.13	0.26	0.43	0.29	0.06	0.04	0.04	0.03	0.05

Table F.2 The water allocation ratio of WD-01

Water season	Monthly level	Allocation ratio											
		May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
High	higher	0.17	0.19	0.23	0.12	0.12	0.03	0.12	0.21	0.18	0.21	0.22	0.23
	high	0.17	0.19	0.23	0.12	0.09	0.04	0.04	0.31	0.19	0.16	0.17	0.23
	medium	0.13	0.15	0.17	0.09	0.06	0.09	0.04	0.31	0.24	0.16	0.18	0.18
	low	0.05	0.15	0.19	0.14	0.11	0.12	0.04	0.31	0.24	0.22	0.24	0.32
	lower	0.06	0.19	0.23	0.00	0.11	0.12	0.04	0.31	0.24	0.22	0.24	0.32
Normal	higher	0.10	0.26	0.21	0.06	0.00	0.06	0.10	0.29	0.01	0.16	0.07	0.13
	high	0.10	0.26	0.21	0.06	0.06	0.03	0.19	0.26	0.17	0.12	0.07	0.13
	medium	0.08	0.19	0.21	0.21	0.12	0.08	0.24	0.22	0.16	0.18	0.23	0.10
	low	0.14	0.19	0.20	0.19	0.09	0.00	0.24	0.22	0.21	0.24	0.30	0.22
	lower	0.20	0.17	0.22	0.12	0.02	0.00	0.24	0.22	0.21	0.24	0.30	0.22
Dry	higher	0.00	0.07	0.22	0.15	0.19	0.20	0.31	0.31	0.07	0.20	0.28	0.17
	high	0.00	0.07	0.22	0.15	0.19	0.24	0.23	0.23	0.05	0.15	0.28	0.17
	medium	0.00	0.07	0.22	0.12	0.03	0.40	0.18	0.18	0.15	0.18	0.21	0.13
	low	0.10	0.19	0.13	0.15	0.11	0.40	0.24	0.24	0.20	0.24	0.28	0.30
	lower	0.13	0.35	0.33	0.15	0.11	0.40	0.24	0.24	0.20	0.24	0.28	0.40
Very Dry	higher	0.25	0.15	0.17	0.06	0.00	0.22	0.10	0.05	0.05	0.20	0.25	0.34
	high	0.25	0.15	0.17	0.06	0.00	0.20	0.10	0.05	0.05	0.20	0.25	0.34
	medium	0.25	0.15	0.17	0.04	0.00	0.15	0.10	0.04	0.04	0.20	0.25	0.34
	low	0.19	0.11	0.13	0.11	0.14	0.20	0.10	0.04	0.17	0.24	0.13	0.34
	lower	0.10	0.12	0.30	0.11	0.14	0.20	0.10	0.04	0.17	0.24	0.13	0.20

Table F.3 The water allocation ratio of WD-02

Water season	Monthly level	Allocation ratio											
		May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
High	higher	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.03	0.02	0.03	0.01
	high	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.05	0.02	0.03	0.01
	medium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.05	0.10	0.03	0.01
	low	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.05	0.10	0.03	0.02
	lower	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.05	0.10	0.03	0.02
Normal	higher	0.04	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.04	0.05
	high	0.04	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.02	0.03	0.04	0.05
	medium	0.04	0.01	0.02	0.01	0.00	0.03	0.00	0.00	0.04	0.02	0.02	0.05
	low	0.01	0.01	0.02	0.01	0.02	0.00	0.00	0.00	0.04	0.02	0.02	0.02
	lower	0.01	0.01	0.02	0.02	0.02	0.00	0.00	0.00	0.04	0.02	0.02	0.02
Dry	higher	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.05	0.03	0.04
	high	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.05	0.03	0.04
	medium	0.05	0.05	0.00	0.00	0.00	0.00	0.01	0.02	0.06	0.05	0.03	0.04
	low	0.01	0.01	0.01	0.02	0.00	0.00	0.01	0.02	0.06	0.05	0.03	0.00
	lower	0.01	0.00	0.00	0.02	0.00	0.00	0.01	0.02	0.06	0.05	0.03	0.00
Very Dry	higher	0.03	0.00	0.02	0.00	0.00	0.00	0.02	0.00	0.10	0.06	0.08	0.04
	high	0.03	0.00	0.02	0.00	0.00	0.00	0.02	0.00	0.10	0.06	0.08	0.04
	medium	0.03	0.00	0.02	0.00	0.00	0.00	0.02	0.00	0.10	0.06	0.08	0.04
	low	0.03	0.00	0.02	0.00	0.00	0.00	0.02	0.02	0.10	0.10	0.02	0.04
	lower	0.03	0.03	0.03	0.00	0.00	0.00	0.02	0.02	0.10	0.10	0.02	0.15

Table F.4 The water allocation ratio of WD-03

Water season	Monthly level	Allocation ratio											
		May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
High	higher	0.02	0.01	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.01	0.03	0.01
	high	0.02	0.01	0.00	0.00	0.02	0.00	0.00	0.00	0.01	0.01	0.03	0.01
	medium	0.02	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.01
	low	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01
	lower	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01
Normal	higher	0.03	0.03	0.01	0.00	0.02	0.00	0.00	0.00	0.01	0.03	0.04	0.03
	high	0.03	0.03	0.01	0.00	0.00	0.01	0.01	0.01	0.03	0.03	0.04	0.03
	medium	0.03	0.03	0.01	0.02	0.01	0.00	0.00	0.01	0.08	0.04	0.02	0.03
	low	0.02	0.01	0.04	0.00	0.01	0.00	0.00	0.01	0.08	0.04	0.02	0.03
	lower	0.03	0.03	0.02	0.08	0.01	0.00	0.00	0.01	0.08	0.04	0.02	0.03
Dry	higher	0.08	0.09	0.04	0.01	0.01	0.00	0.01	0.02	0.14	0.17	0.09	0.06
	high	0.08	0.09	0.04	0.01	0.01	0.00	0.01	0.02	0.14	0.17	0.09	0.06
	medium	0.08	0.09	0.04	0.01	0.00	0.00	0.02	0.02	0.09	0.11	0.09	0.06
	low	0.04	0.04	0.04	0.03	0.00	0.00	0.02	0.02	0.09	0.11	0.09	0.07
	lower	0.04	0.00	0.01	0.03	0.00	0.00	0.02	0.02	0.09	0.11	0.09	0.07
Very Dry	higher	0.54	0.03	0.08	0.02	0.00	0.00	0.02	0.01	0.08	0.14	0.12	0.13
	high	0.54	0.03	0.08	0.02	0.00	0.00	0.02	0.01	0.08	0.14	0.12	0.13
	medium	0.54	0.03	0.08	0.02	0.00	0.00	0.02	0.01	0.08	0.14	0.12	0.13
	low	0.54	0.03	0.08	0.05	0.50	0.00	0.02	0.01	0.11	0.13	0.06	0.13
	lower	0.05	0.22	0.20	0.05	0.50	0.00	0.02	0.01	0.11	0.13	0.06	0.09

Table F.5 The water allocation ratio of WD-04

Water season	Monthly level	Allocation ratio											
		May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
High	higher	0.07	0.10	0.08	0.15	0.22	0.07	0.02	0.05	0.15	0.14	0.13	0.16
	high	0.06	0.10	0.01	0.15	0.38	0.12	0.03	0.04	0.08	0.11	0.05	0.11
	medium	0.06	0.10	0.01	0.15	0.38	0.12	0.00	0.07	0.15	0.11	0.05	0.11
	low	0.06	0.10	0.01	0.15	0.18	0.03	0.00	0.07	0.15	0.24	0.16	0.11
	lower	0.08	0.10	0.10	0.19	0.10	0.03	0.00	0.07	0.15	0.24	0.16	0.34
Normal	higher	0.08	0.10	0.07	0.09	0.10	0.03	0.00	0.07	0.15	0.24	0.16	0.34
	high	0.14	0.08	0.11	0.21	0.44	0.21	0.01	0.08	0.17	0.15	0.06	0.14
	medium	0.14	0.08	0.11	0.21	0.11	0.06	0.01	0.06	0.17	0.15	0.06	0.14
	low	0.14	0.08	0.11	0.03	0.08	0.02	0.04	0.01	0.16	0.18	0.15	0.14
	lower	0.08	0.19	0.15	0.09	0.02	0.00	0.04	0.01	0.16	0.18	0.15	0.07
Dry	higher	0.34	0.01	0.05	0.03	0.00	0.00	0.04	0.01	0.16	0.18	0.15	0.07
	high	0.07	0.05	0.06	0.03	0.03	0.00	0.00	0.01	0.15	0.00	0.12	0.08
	medium	0.07	0.05	0.06	0.03	0.03	0.01	0.00	0.01	0.15	0.00	0.12	0.08
	low	0.07	0.05	0.06	0.03	0.12	0.00	0.00	0.05	0.17	0.20	0.12	0.08
	lower	0.10	0.13	0.04	0.05	0.01	0.00	0.00	0.05	0.17	0.20	0.12	0.32
Very Dry	higher	0.10	0.01	0.20	0.05	0.01	0.00	0.00	0.05	0.17	0.20	0.12	0.32
	high	0.35	0.02	0.00	0.11	0.09	0.01	0.00	0.03	0.16	0.33	0.23	0.06
	medium	0.35	0.02	0.00	0.11	0.09	0.00	0.00	0.03	0.16	0.33	0.23	0.06
	low	0.35	0.02	0.00	0.11	0.09	0.00	0.00	0.03	0.16	0.33	0.23	0.06
	lower	0.35	0.02	0.00	0.02	0.01	0.00	0.00	0.01	0.10	0.24	0.28	0.06

Table F.6 The water allocation ratio of WD-05

Water season	Monthly level	Allocation ratio											
		May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
High	higher	0.21	0.14	0.02	0.13	0.02	0.10	0.06	0.08	0.23	0.13	0.23	0.18
	high	0.21	0.14	0.02	0.13	0.02	0.02	0.02	0.12	0.14	0.13	0.23	0.18
	medium	0.21	0.14	0.02	0.13	0.20	0.33	0.02	0.12	0.14	0.17	0.13	0.18
	low	0.18	0.14	0.13	0.09	0.23	0.33	0.02	0.12	0.14	0.17	0.13	0.01
	lower	0.18	0.14	0.16	0.16	0.23	0.33	0.02	0.12	0.14	0.17	0.13	0.01
Normal	higher	0.21	0.16	0.16	0.09	0.00	0.08	0.15	0.08	0.10	0.14	0.17	0.18
	high	0.21	0.16	0.16	0.09	0.09	0.05	0.12	0.20	0.13	0.14	0.17	0.18
	medium	0.21	0.16	0.16	0.12	0.11	0.27	0.26	0.14	0.19	0.13	0.17	0.18
	low	0.17	0.10	0.14	0.10	0.14	0.38	0.26	0.14	0.19	0.13	0.17	0.07
	lower	0.18	0.22	0.13	0.21	0.43	0.38	0.26	0.14	0.19	0.13	0.17	0.07
Dry	higher	0.06	0.02	0.00	0.09	0.05	0.03	0.11	0.00	0.36	0.26	0.15	0.14
	high	0.06	0.02	0.00	0.09	0.05	0.08	0.11	0.00	0.36	0.26	0.15	0.14
	medium	0.06	0.02	0.00	0.09	0.09	0.11	0.18	0.10	0.14	0.17	0.15	0.14
	low	0.19	0.16	0.13	0.16	0.05	0.11	0.18	0.10	0.14	0.17	0.15	0.08
	lower	0.19	0.13	0.06	0.16	0.05	0.11	0.18	0.10	0.14	0.17	0.15	0.08
Very Dry	higher	0.06	0.01	0.18	0.26	0.19	0.01	0.28	0.11	0.17	0.16	0.23	0.06
	high	0.06	0.01	0.18	0.26	0.19	0.01	0.28	0.11	0.17	0.16	0.23	0.06
	medium	0.06	0.01	0.18	0.26	0.19	0.34	0.28	0.11	0.17	0.16	0.23	0.06
	low	0.06	0.01	0.18	0.12	0.03	0.34	0.28	0.00	0.12	0.18	0.19	0.06
	lower	0.18	0.11	0.24	0.12	0.03	0.34	0.28	0.00	0.12	0.18	0.19	0.34

Table F.7 The water allocation ratio of Chao Praya Irrigation Project

Water season	Monthly level	Allocation ratio											
		May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
High	higher	0.34	0.38	0.35	0.27	0.21	0.12	0.17	0.41	0.87	0.86	0.81	0.86
	high	0.34	0.38	0.35	0.49	0.49	0.58	0.37	0.41	0.87	0.86	0.81	0.86
	medium	0.72	0.50	0.67	0.65	0.49	0.58	0.88	0.53	0.87	0.86	0.81	0.86
	low	0.84	0.75	0.85	0.65	0.49	0.58	0.88	0.76	0.87	0.86	0.84	0.89
	lower	0.84	0.75	0.85	0.65	0.49	0.58	0.88	0.85	0.84	0.86	0.86	0.85
Normal	higher	0.60	0.28	0.34	0.24	0.33	0.35	0.19	0.28	0.57	0.44	0.60	0.81
	high	0.60	0.44	0.50	0.64	0.72	0.63	0.63	0.28	0.72	0.66	0.71	0.81
	medium	0.83	0.60	0.70	0.81	0.72	0.63	0.90	0.71	0.87	0.89	0.82	0.81
	low	0.80	0.79	0.79	0.81	0.72	0.63	0.78	0.66	0.87	0.81	0.81	0.80
	lower	0.82	0.91	0.79	0.81	0.72	0.63	0.78	0.85	0.72	0.81	0.81	0.82
Dry	higher	0.65	0.40	0.58	0.42	0.37	0.17	0.16	0.17	0.73	0.84	0.83	0.80
	high	0.65	0.43	0.57	0.60	0.72	0.69	0.75	0.17	0.73	0.84	0.83	0.80
	medium	0.73	0.80	0.66	0.80	0.72	0.69	0.75	0.63	0.73	0.84	0.81	0.80
	low	0.73	0.66	0.77	0.84	0.72	0.69	0.75	0.79	0.73	0.84	0.78	0.80
	lower	0.74	0.78	0.70	0.84	0.72	0.69	0.75	0.79	0.69	0.73	0.86	0.74
Very	higher	0.08	0.38	0.40	0.60	0.38	0.34	0.81	0.67	0.74	0.75	0.77	0.74
	high	0.08	0.16	0.58	0.72	0.80	0.34	0.81	0.67	0.74	0.75	0.77	0.74
	medium	0.78	0.50	0.77	0.72	0.80	0.34	0.86	0.78	0.74	0.75	0.77	0.74
	low	0.68	0.83	0.73	0.72	0.80	0.34	0.86	0.81	0.74	0.75	0.66	0.70
	lower	0.68	0.67	0.69	0.72	0.80	0.34	0.86	0.81	0.61	0.63	0.63	0.54

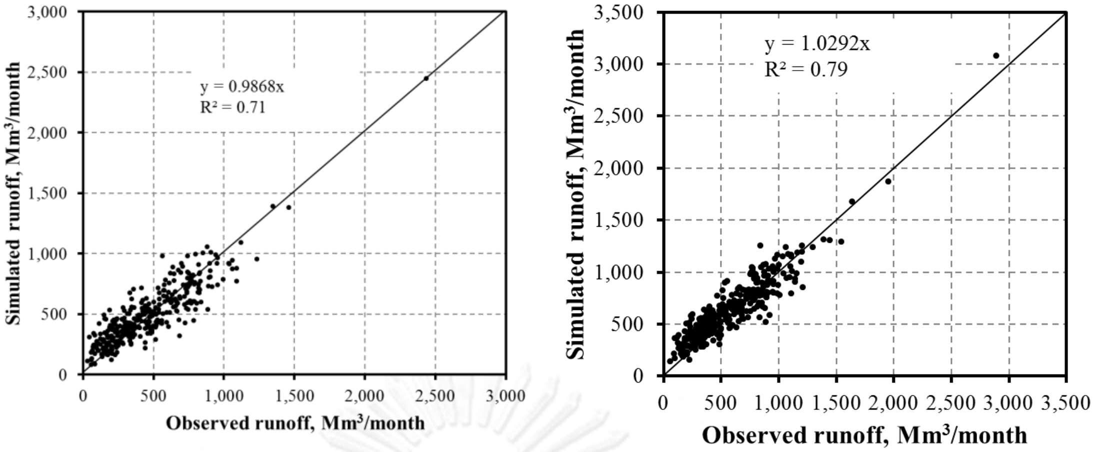
F.2 Water balance model calibration

The water balance model was calibrated in year 1979 – 2006. The side flow from the rainfall-runoff model and actual release of Sirikit Dam would be used as the input variables in this calibrating stage. Hence, the water balance model was necessary to calibrate the flow volume that will be considered on the net flow at control point. The control points locate on the main Nan river include N.12A at Ban Hat Phai, Uttaradit, N.60 at Ban Hat Song Khwae, Uttaradit, N.27A at Phrom Phiram, Phitsanulok, N.5A at Muang, Phitsanulok, N.7A at Ban Rat Chang Kwan, Phichit, N.67 at Ban Goey Chai, Nakornsawan and C.2 at Ban Phai Lom, Nakornsawan.

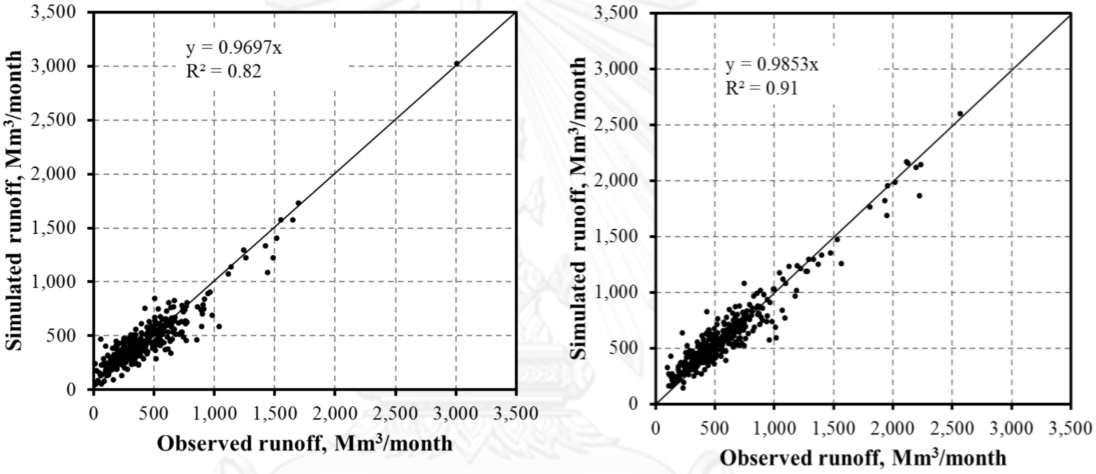
The net flow of each control would be balancing the water extraction volume and the side flow. Here, the water extraction is the unknown values, so the solving in this stage is to attempt balancing the net flow along the main river in the water resources system. Due to the observed runoff data is quite incompletely in some years, the data extrapolation will be used to deal with this problem. The data extrapolation is to find some relationship between each control point by using linear regression method. The comparison of observed and simulated runoff of 6 runoff stations under the downstream of Sirikit Dam (on the main Nan River), C.2 and C.13 show as Figure F.2 and F.3, respectively. The goodness of fit test of water balance model calibration was shown as Table F.6. The correlation (R^2) is in range 0.79 – 0.96, the root mean square error (RMSE) is in range 116.71 – 505.19 MCM/month and the standard error (SE) is in range 113.87 – 492.60 MCM/month.

Table F.6 The goodness of fit test of water balance model in model calibration stage

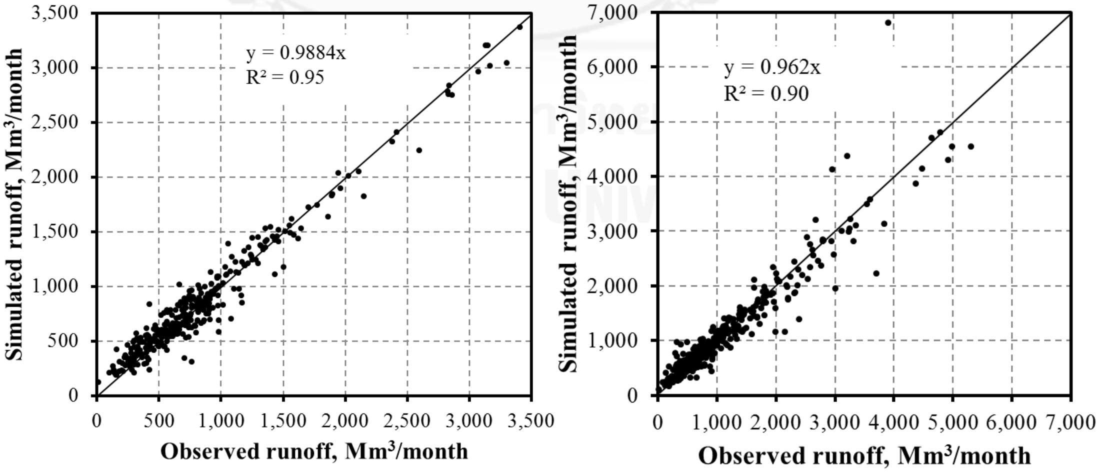
Runoff station	R^2	RMSE	SE
N.12A	0.71	133.28	130.37
N.60	0.79	138.53	128.58
N.27A	0.82	116.71	115.29
N.5A	0.91	115.65	113.87
N.7A	0.95	121.86	121.40
N.67	0.90	294.75	296.23
C.2	0.89	505.19	492.60
C.13	0.75	739.82	653.96



(a)N.12A (b) N.60



(c) N.27A (d) N.5A



(e) N.7A (f) N.67

Figure F.2 The comparison of observed and simulated runoff at the control point of Nan River in year 1979 - 2006

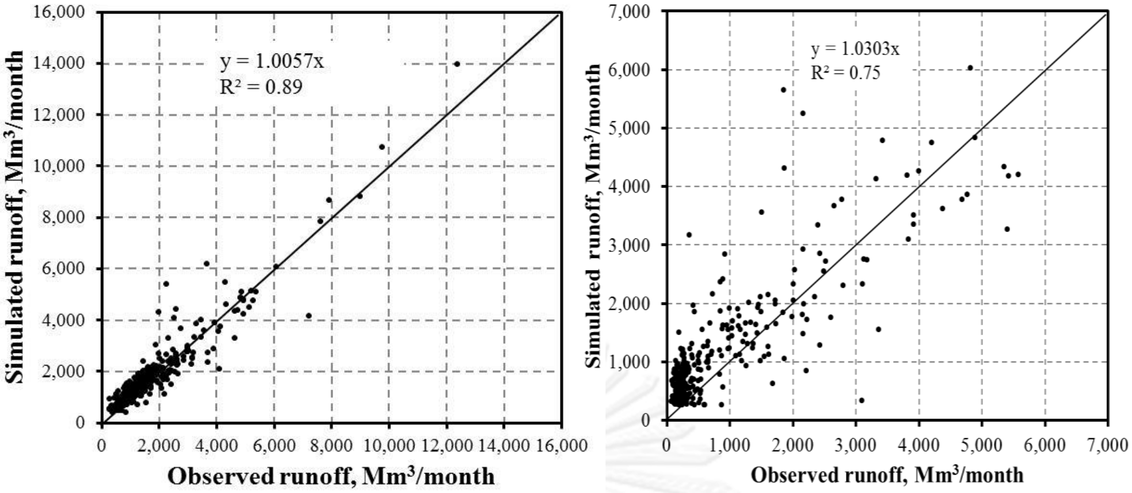


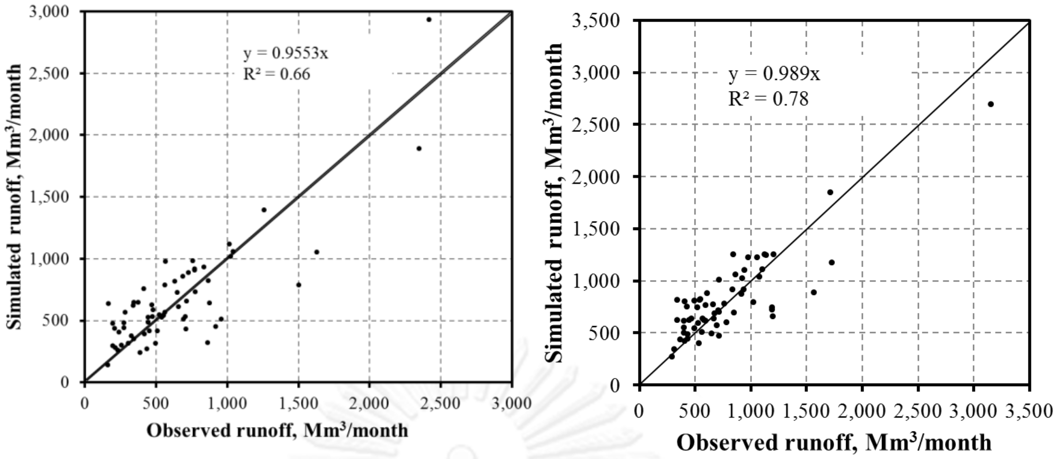
Figure F.3 The comparison of observed and simulated runoff at C.2 and C.13 in year 1979 - 2006

F.3 Water balance model validation

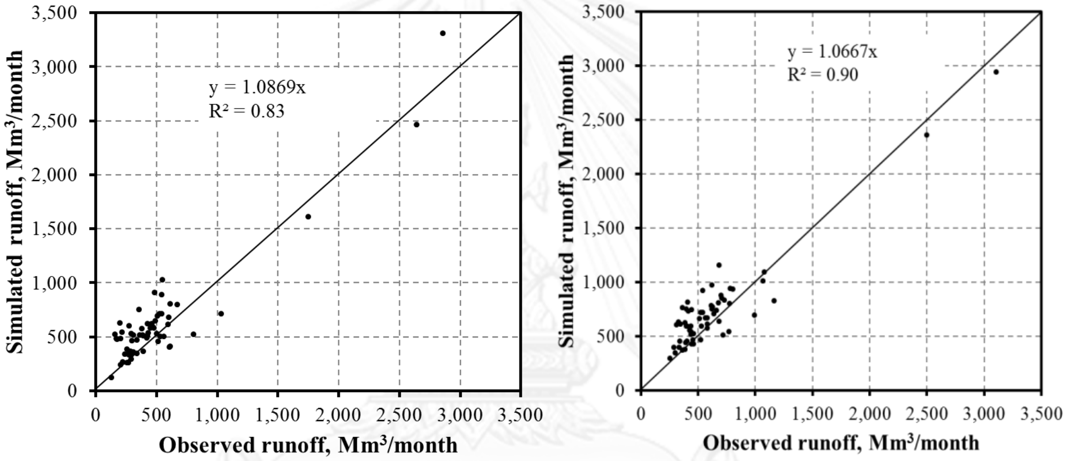
The water balance model could be verified by balancing the runoff or net flow in year 2007 – 2011. The solving algorithm was used the same method as model calibration. From the results, this water balance model can be implied to use for balancing the net flow in this study as well. The comparison of observed and simulated runoff of 6 runoff stations under the downstream of Sirikit Dam (on the main Nan River), C.2 and C.13 are shown as Figure F.4 and F.5, respectively. The goodness of fit indices of water balance model validation was shown as Table F.7. The correlation (R^2) is in range 0.71 – 0.95, the root mean square error (RMSE) is in range 82.24 – 254.35 MCM/month and the standard error (SE) is in range 169.15 – 521.60 MCM/month.

Table F.7 The goodness of fit test of water balance in model validation stage

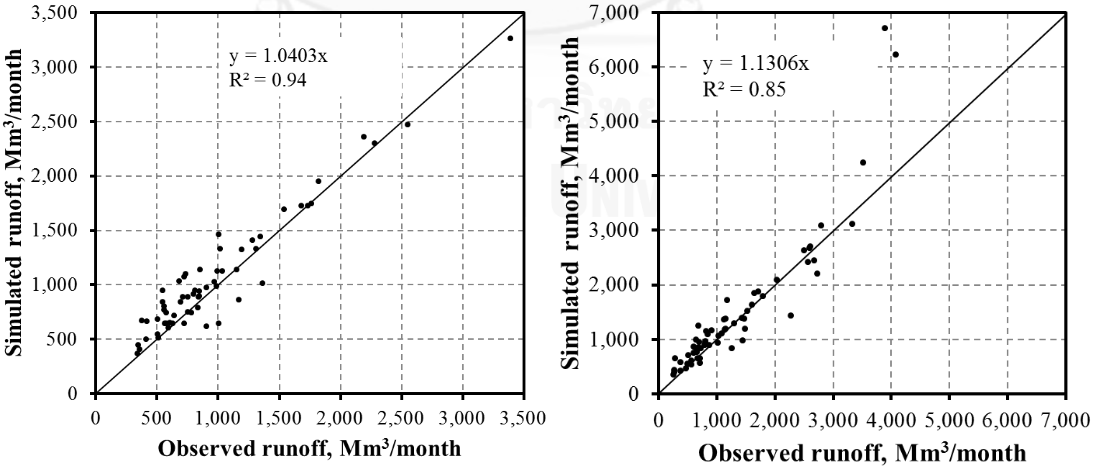
Runoff station	R^2	RMSE	SE
N.12A	0.66	104.89	242.03
N.60	0.78	105.78	243.92
N.27A	0.83	86.95	169.15
N.5A	0.90	84.73	169.27
N.7A	0.93	82.24	173.78
N.67	0.85	220.53	365.63
C.2	0.93	254.35	521.60
C.13	0.81	962.93	867.10



(a) N.12A (b) N.60

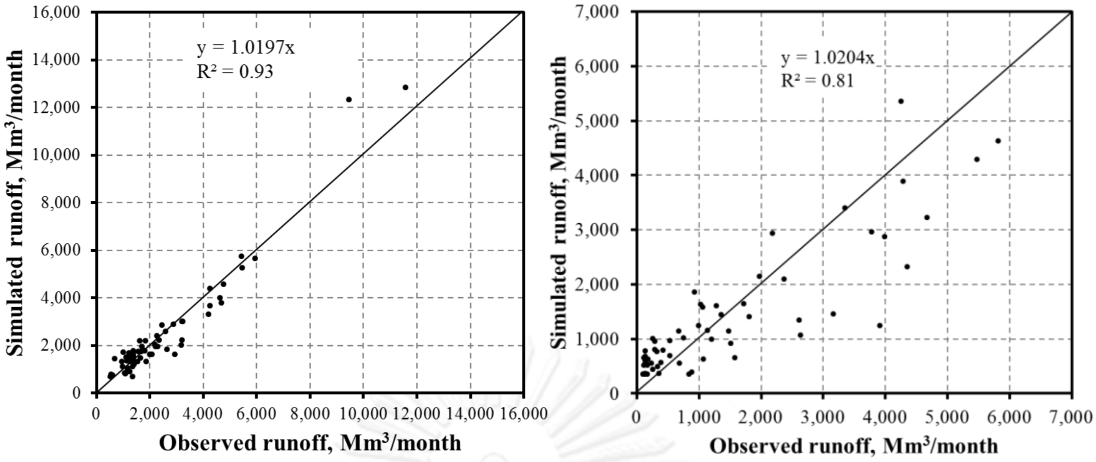


(c) N.27A (d) N.5A



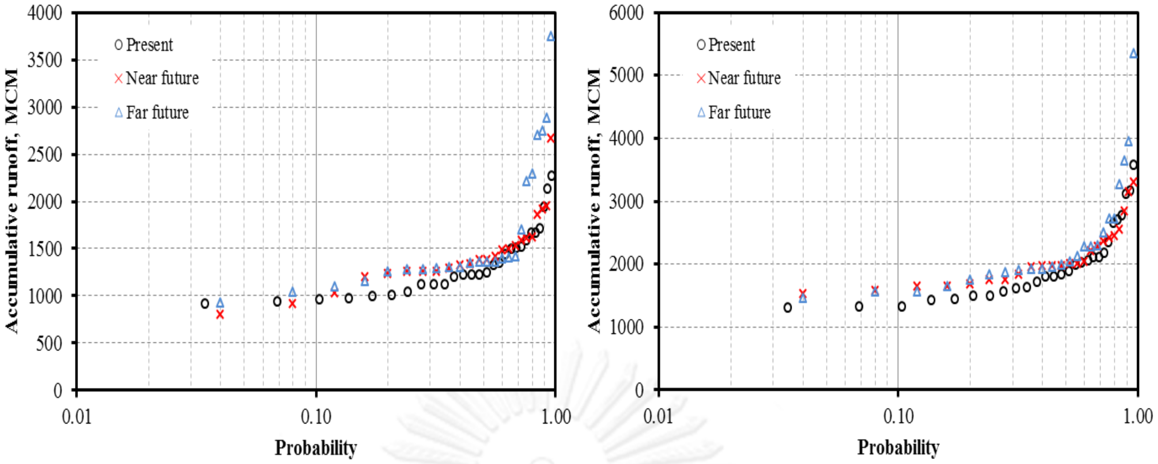
(e) N.7A (f) N.67

Figure F.4 The comparison of observed and simulated runoff at the control point of Nan River in year 2007 – 2011

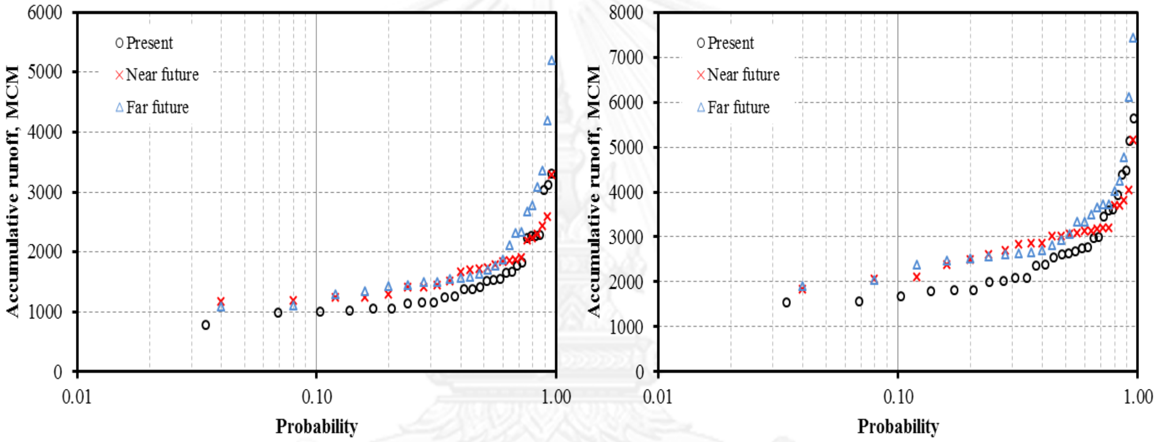


(g) C.2 (h) C.13

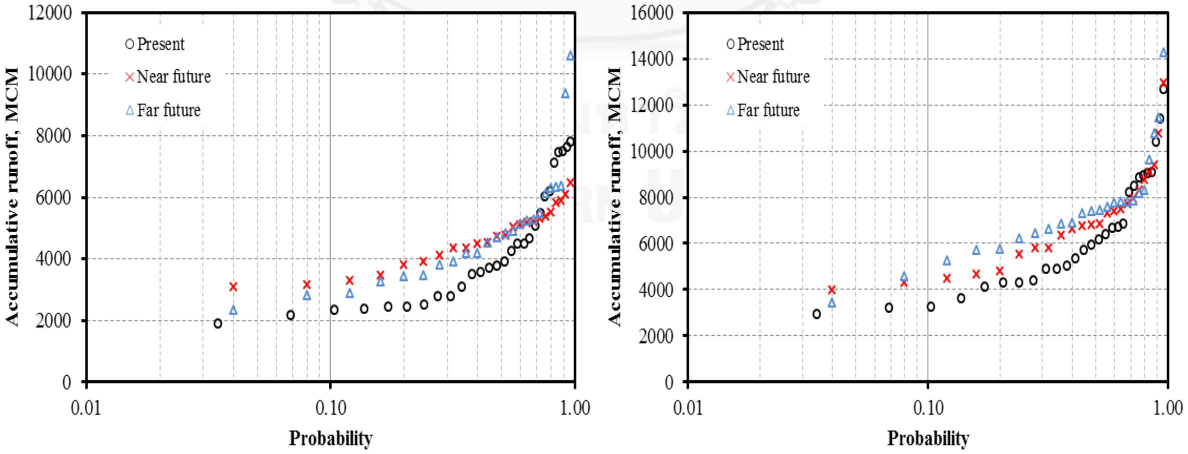
Figure F.5 The comparison of observed and simulated runoff at C.2 in year 2007 – 2011



(a) N.12A (b) N.60

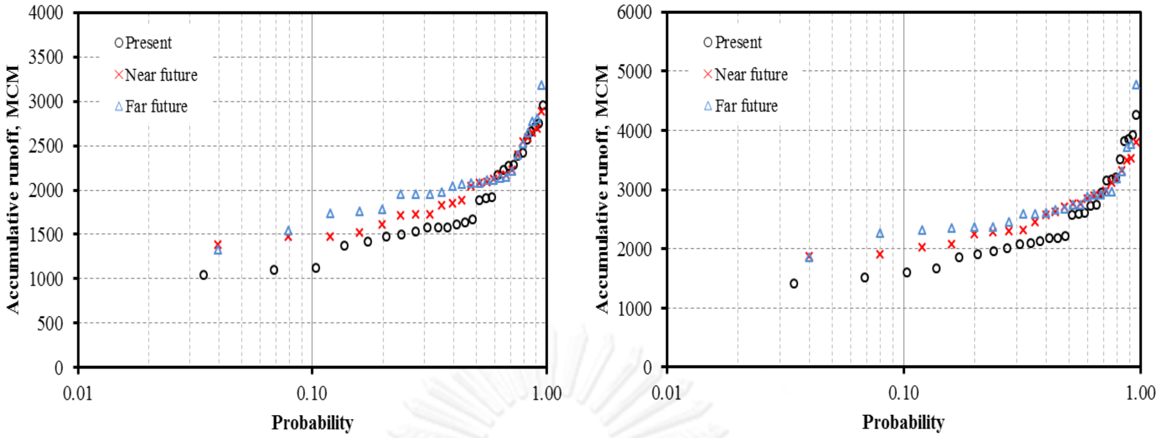


(c) N.27A (d) N.5A

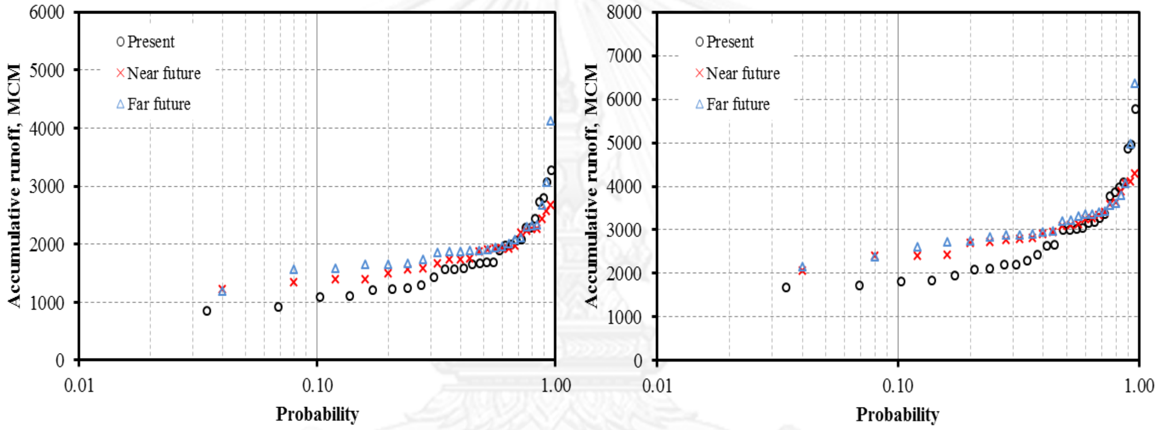


(e) N.7A (f) N.67

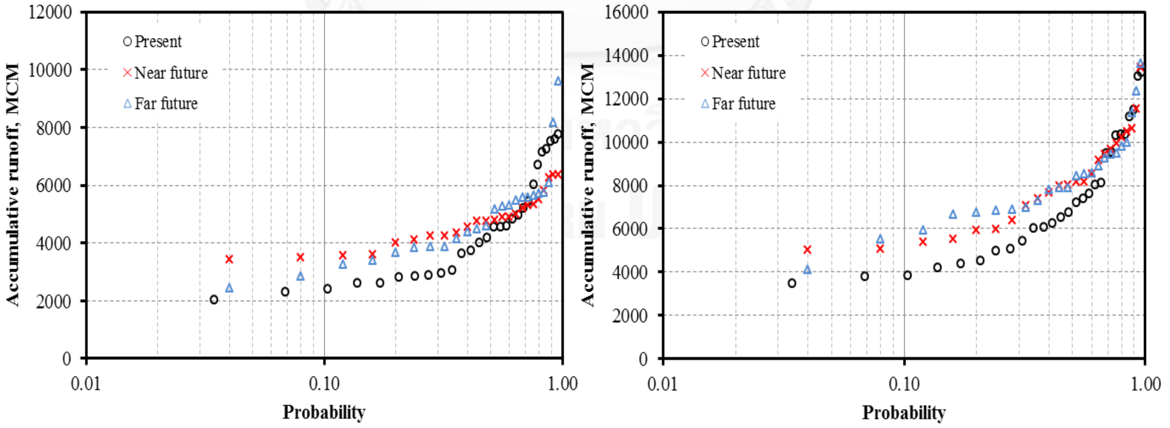
Figure F.6 The probability of annual accumulative runoff at the control points of Nan River by general reservoir operation



(a) N.12A (b) N.60

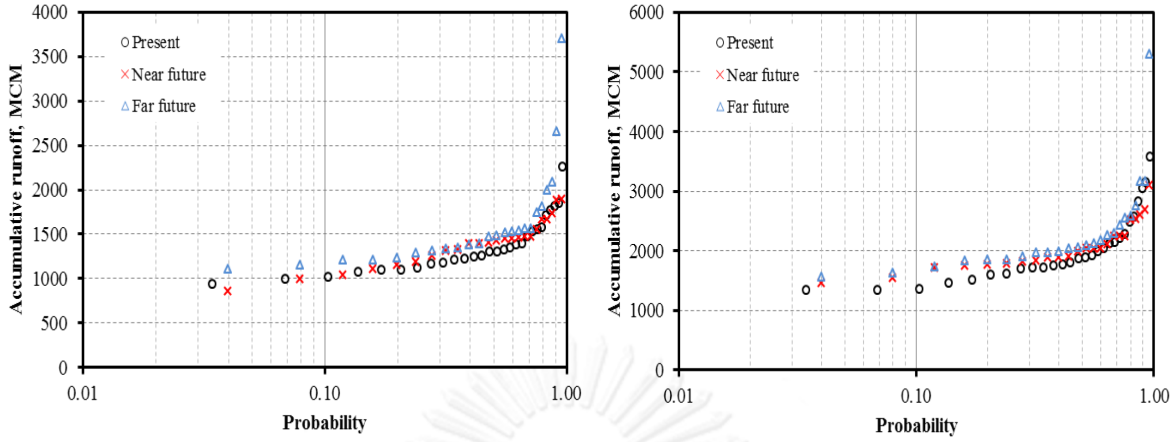


(c) N.27A (d) N.5A



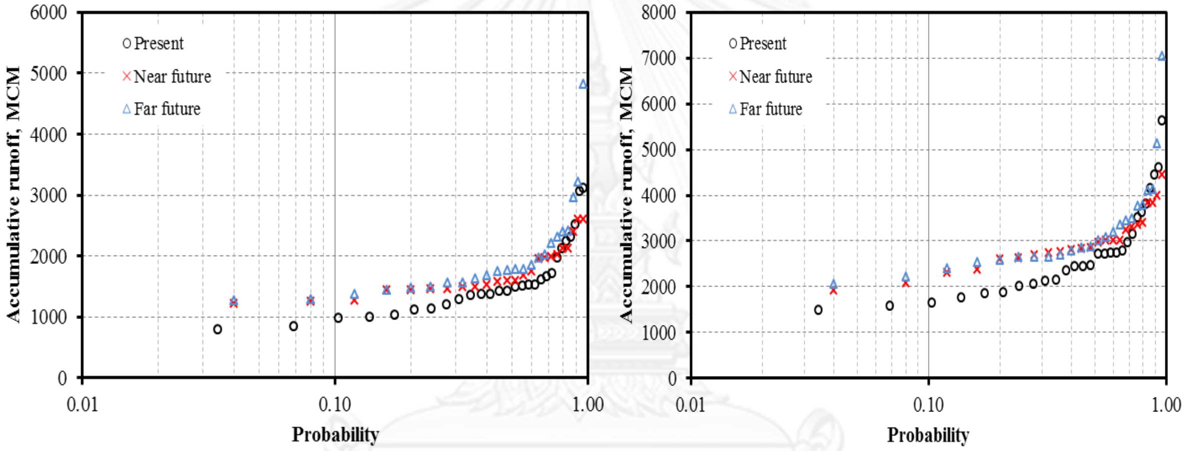
(e) N.7A (f) N.67

Figure F.7 The probability of annual accumulative runoff at the control points of Nan River by flood reservoir operation



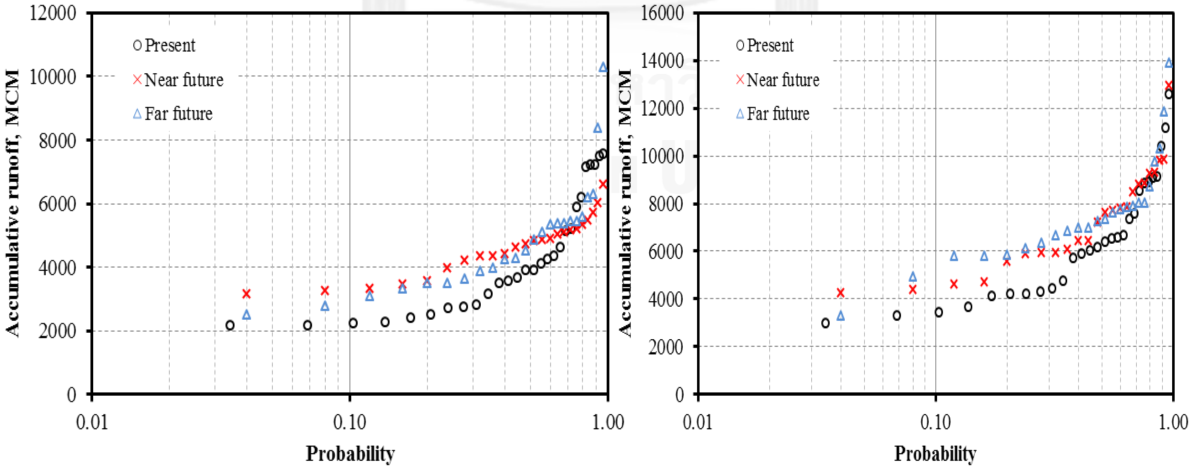
(a) N.12A

(b) N.60



(c) N.27A

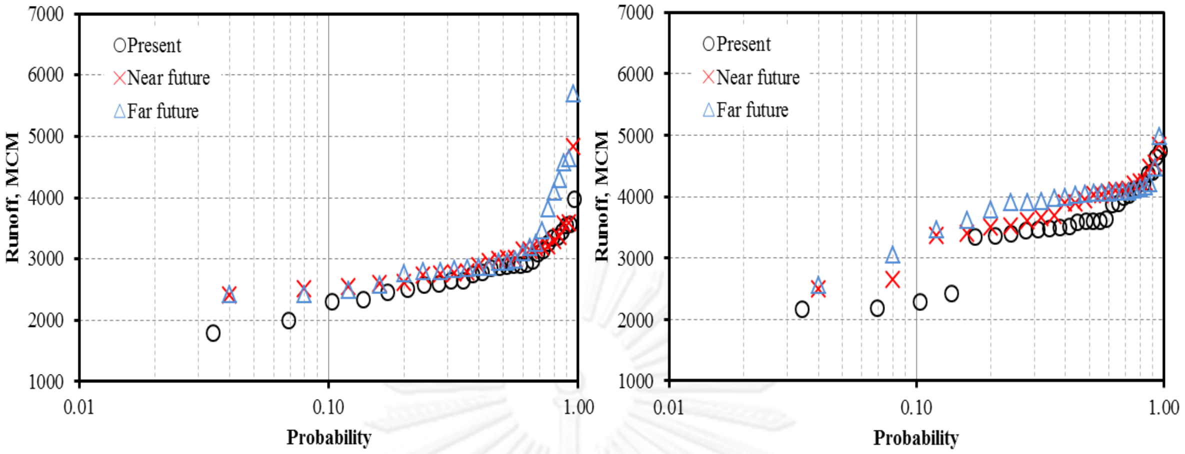
(d) N.5A



(e) N.7A

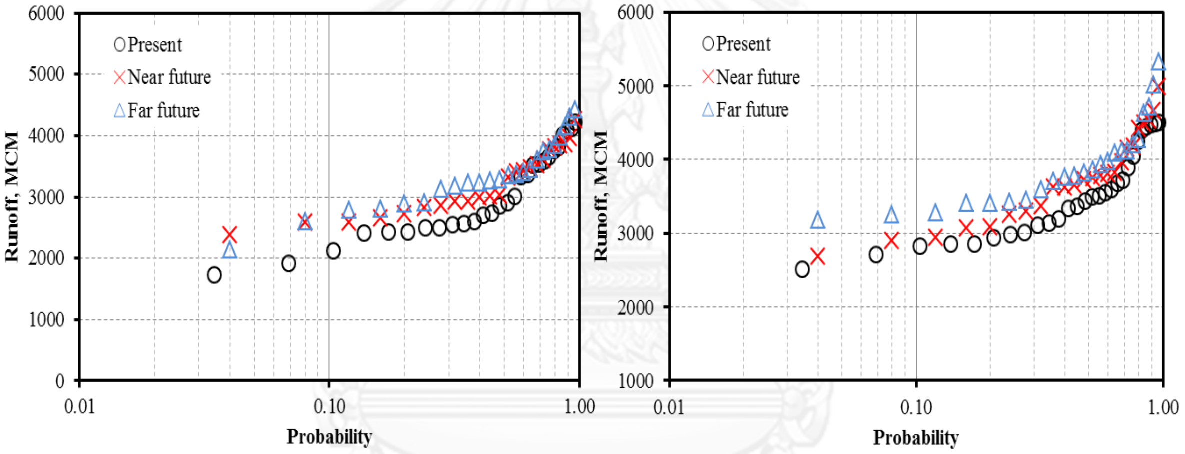
(f) N.67

Figure F.8 The probability of annual accumulative runoff at the control points of Nan River by ANFIS* reservoir operation



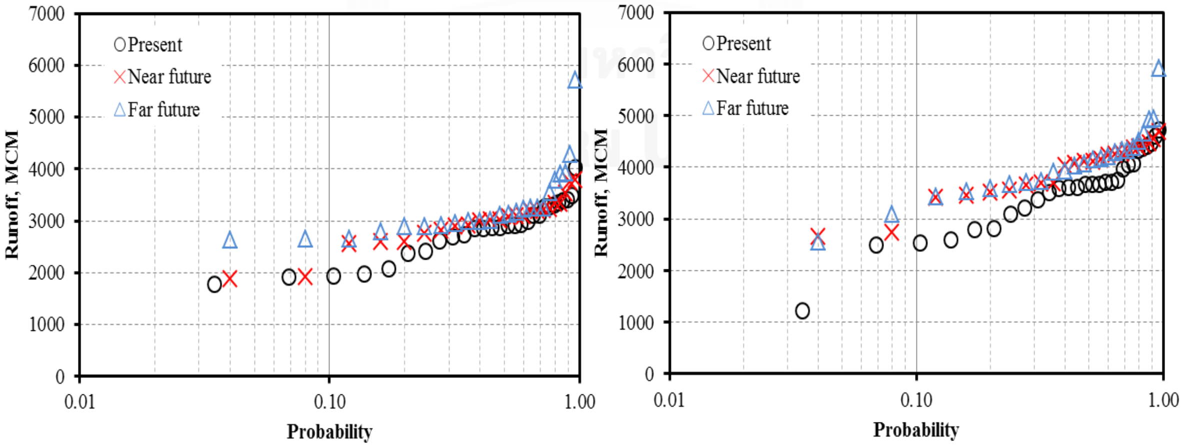
(a) General – wet season

(b) General – dry season



(c) Flood – wet season

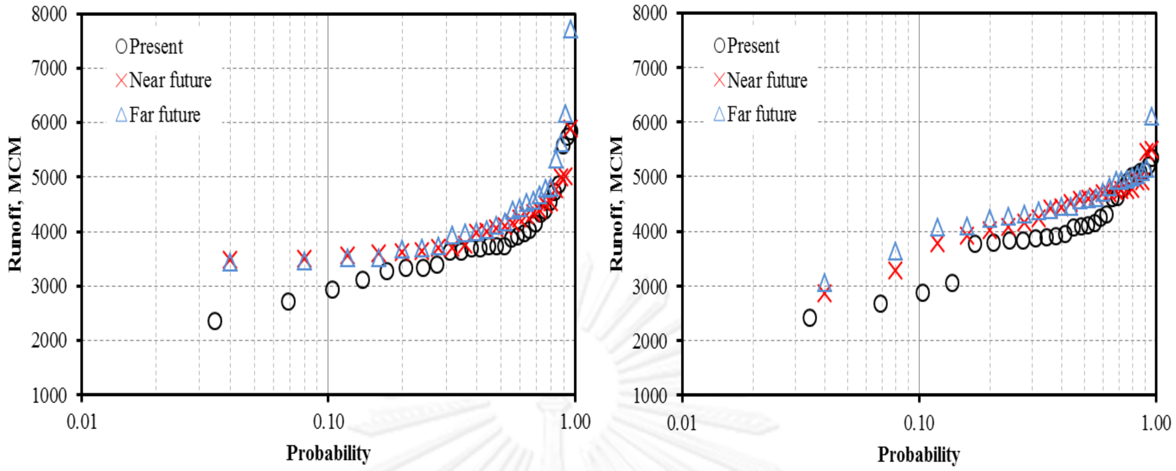
(d) Flood – dry season



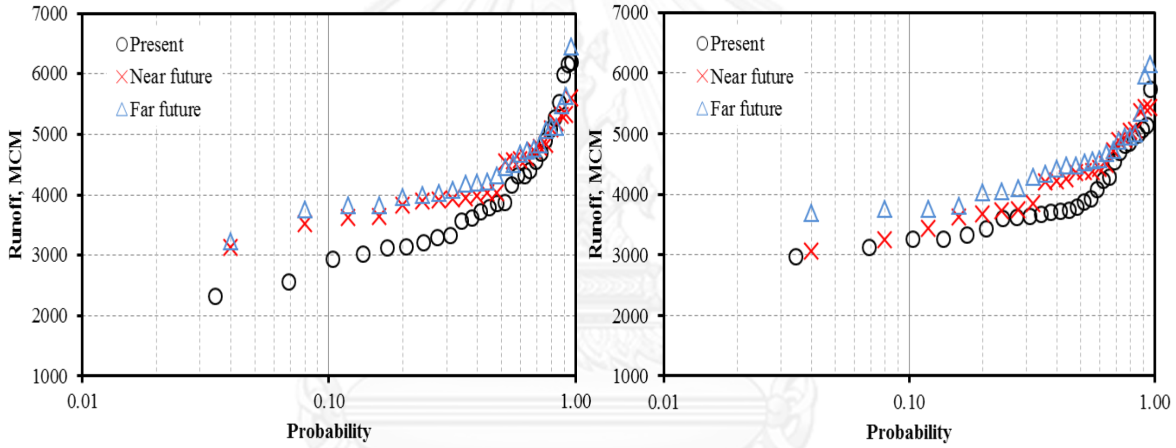
(e) ANFIS* – wet season

(f) ANFIS* – dry season

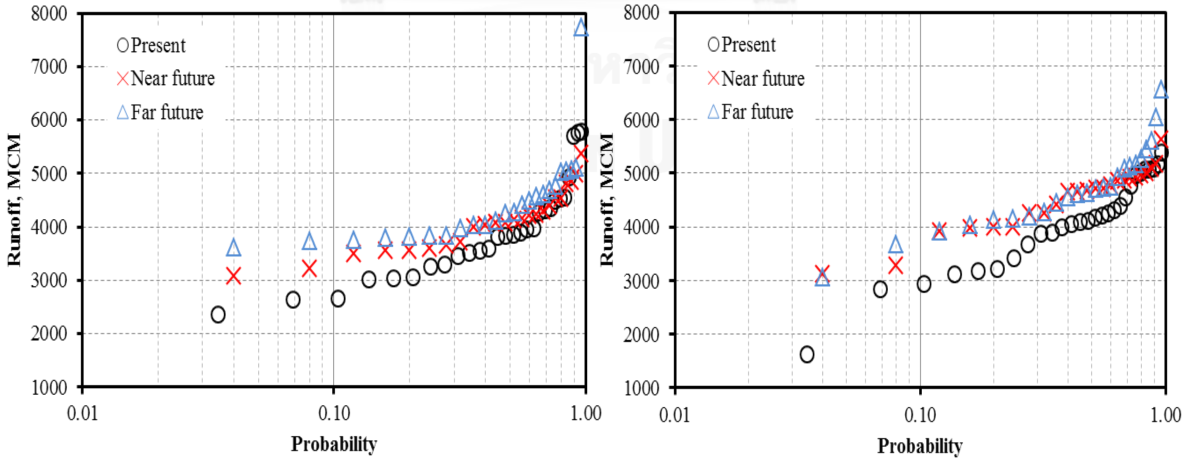
Figure F.9 Probability of seasonal runoff of N.12A by general, flood, ANFIS* reservoir operation



(a) General – wet season (b) General – dry season

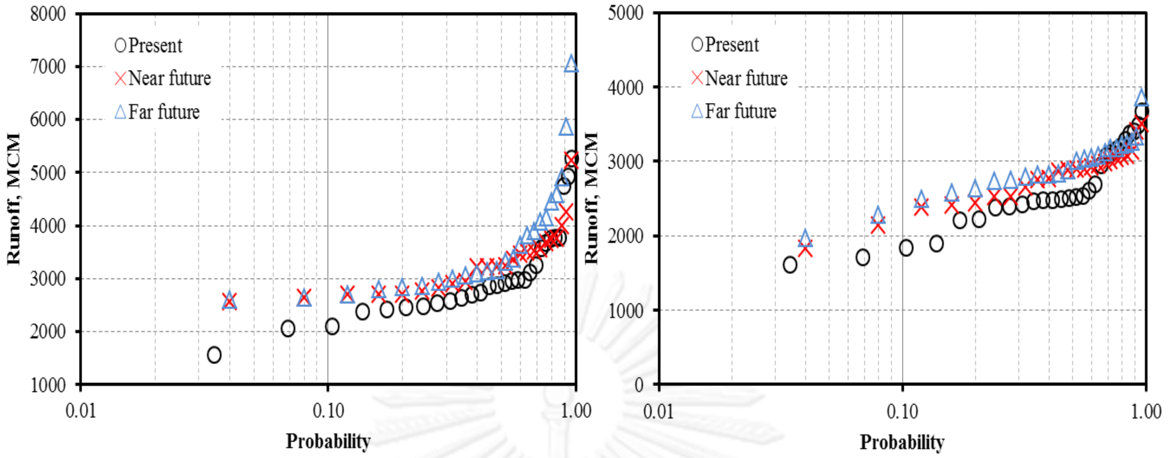


(c) Flood – wet season (d) Flood – dry season

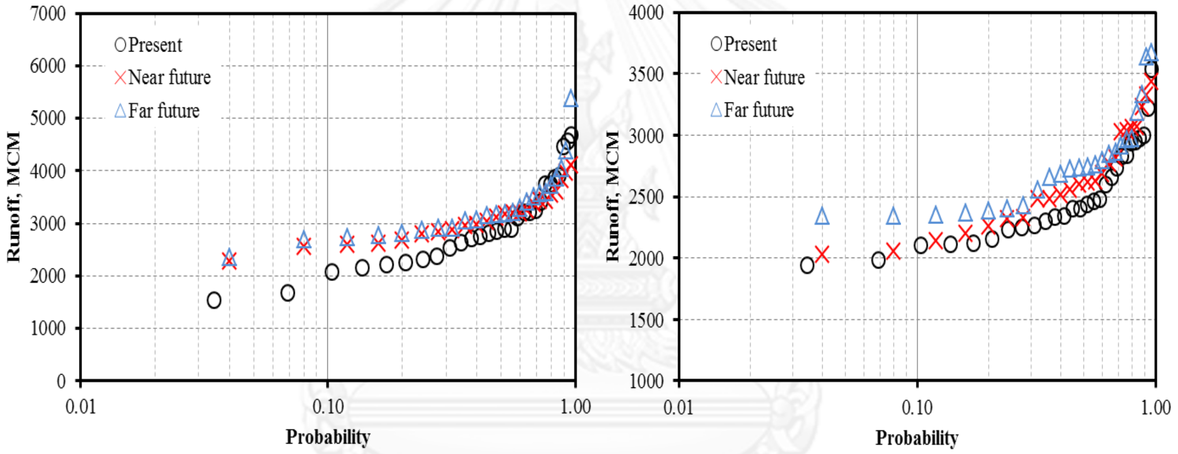


(e) ANFIS* – wet season (f) ANFIS* – dry season

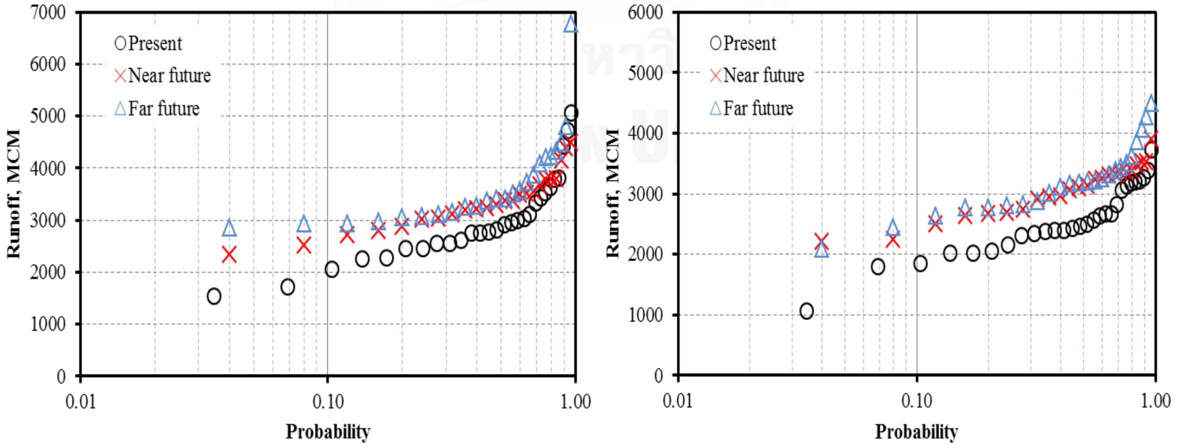
Figure F.10 Probability of seasonal runoff of N.60 by general, flood, ANFIS* reservoir operation



(a) General – wet season
(b) General – dry season

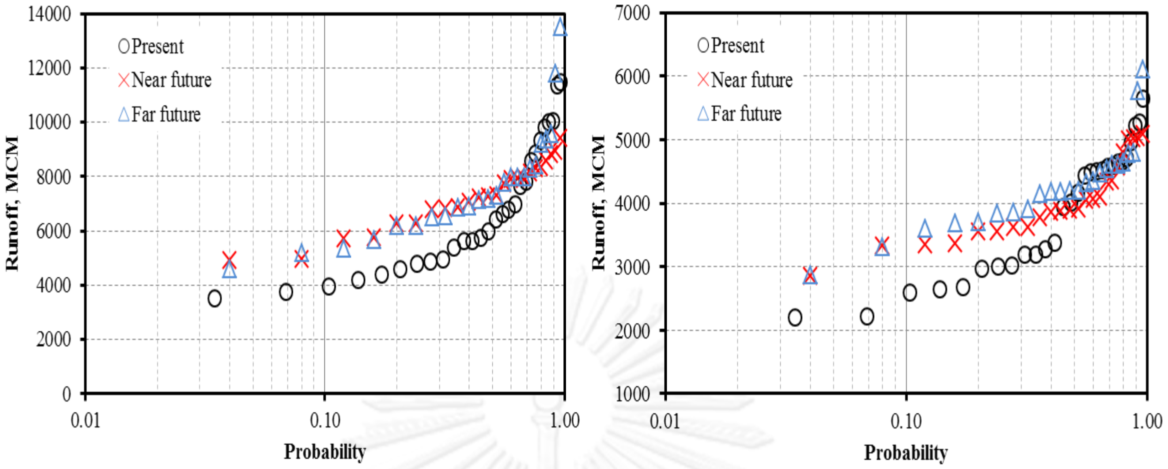


(c) Flood – wet season
(d) Flood – dry season

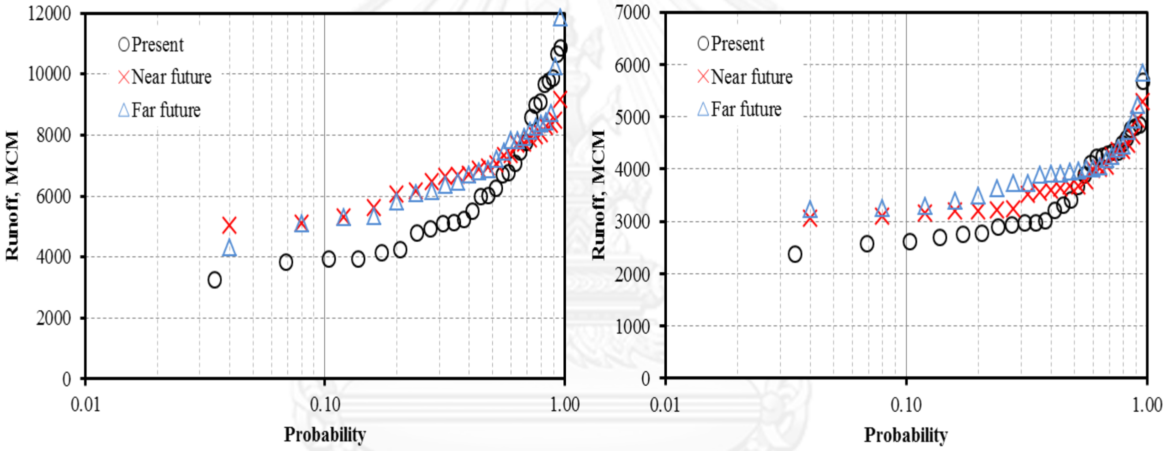


(e) ANFIS* – wet season
(f) ANFIS* – dry season

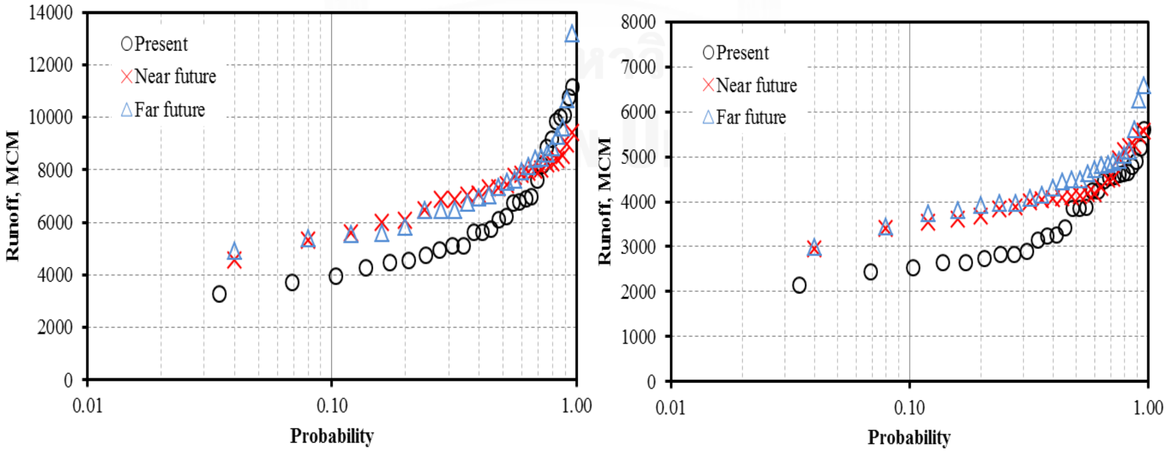
Figure F.11 Probability of seasonal runoff of N.27A by general, flood, ANFIS* reservoir operation



(a) General – wet season (b) General – dry season

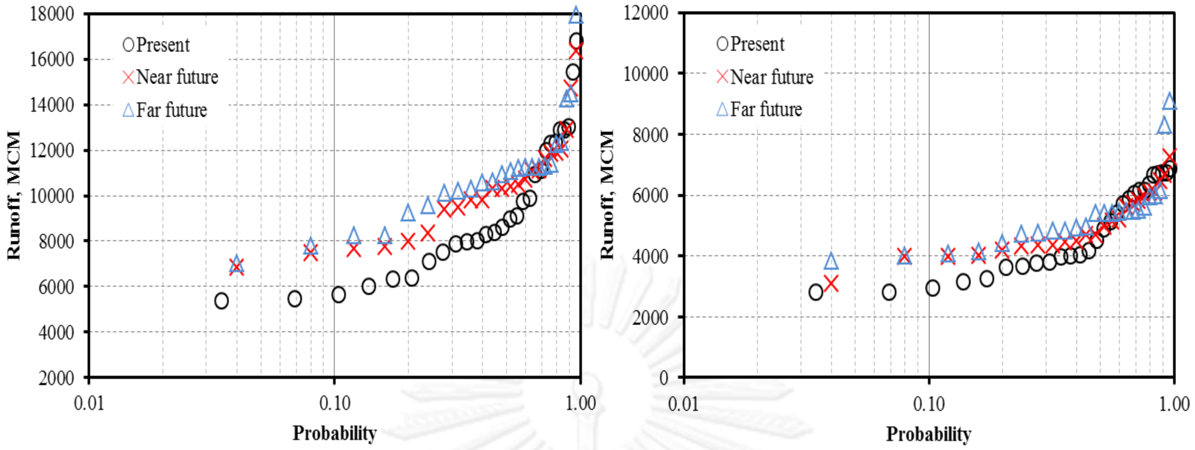


(c) Flood – wet season (d) Flood – dry season

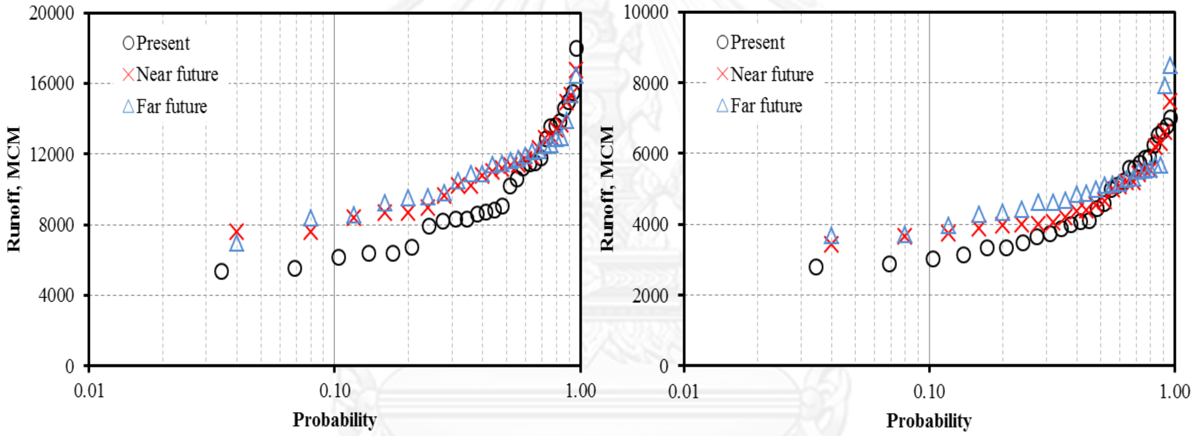


(e) ANFIS* – wet season (f) ANFIS* – dry season

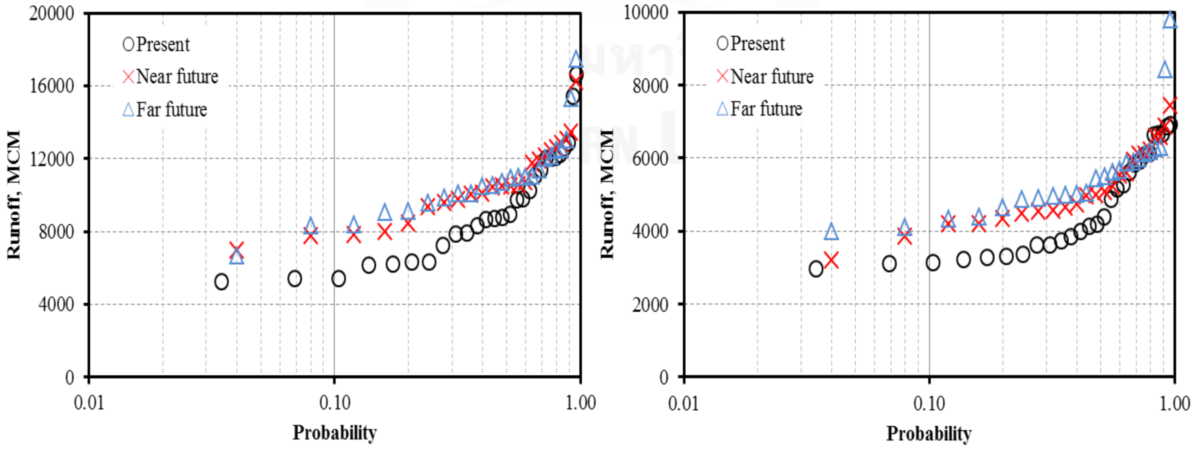
Figure F.12 Probability of seasonal runoff of N.7A by general, flood, ANFIS* reservoir operation



(a) General – wet season (b) General – dry season



(c) Flood – wet season (d) Flood – dry season



(e) ANFIS* – wet season (f) ANFIS* – dry season

Figure F.13 Probability of seasonal runoff of N.67 by general, flood, ANFIS* reservoir operation

Appendix G
Reservoir operation model program

Appendix G

Reservoir operation model program

G.1 ANFIS generation procedure

1) Prepare the state variables files and load data into the ANFIS toolbox in the MATLAB program.

2) Generate ANFIS according to the ANFIS theory in Chapter 4 by ANFIS toolbox in the MATLAB program follows as:

2.1) Generate FIS by following the steps as:

- Select the grid partition as the generating FIS method.
- For the input variables, assign the number of membership function (MFs) to each input variable, and then select the trapezoidal MF type.
- For the output variable, select the linear MF type.

2.2) Select the hybrid optimization method.

2.3) FIS properties :

- For And method, select “prod”.
- For Or method, select “probor”.
- For the defuzzification, select the weighted average method.
- For FIS type, select “Sugeno FIS”.

2.4) For the fuzzy rule base, select connection as “and”.

3) Evaluate the ANFIS release functions by incorporating this ANFIS release functions into reservoir operation model, and then verify the release results by the goodness of fit test indices such as the correlation (R2), the root mean square error (RMSE) and the standard error. The ANFIS release functions will call as the existing reservoir operation rule.

G.2 Reservoir operation model

```
% Water Balance for Sirikit Dam
%
% Input Variables for reservoir balance
% M1 = Month start from May
% M2 = Month start from June
% Inf1 = Inflow of Sirikit Dam, MCM/month
% Sfo1 = Side flow from Nan Pad river basin and Lower Nan part 4/1, MCM/month
% Rf11 = rainfall at surface are of Sirikit dam
% Ei1  = Evaporation, mm/month
% Rf21 = rainfall at downstream of Nan river basin area
% Wu1 = Water demand unit of rice in Phitsanulok Project, MCM/month
% Wu2 = Water demand unit of crop in Phitsanulok Project, MCM/month
% Ri = Release, MCM/day
% Rf = Rainfall, mm
%
% Water Balance Equation
%
% Sto = Stp + Inf - Ri - Ei
%
clear all; clc; close all;

% reservoir water balance for Sirikit dam

skdata = load('Input_SK_wd.txt','%f');
M1  = skdata(:,1);
M2  = skdata(:,2);
```

```
Inf1 = skdata(:,3);
Sfo1 = skdata(:,4);
Rf11 = skdata(:,5);
Ei1  = skdata(:,6);
Rf21 = skdata(:,7);
Wu1  = skdata(:,8);
Wu2  = skdata(:,9);


% Type1 = Type of water season for reservoir release function
% Type21 = Type of water season for identify cultivated area
% Type22 = Sub Type of water season for identify cultivated area
%

Type1 = zeros(301,1);
Type21 = zeros(301,1);
Type22 = zeros(301,1);
Ag    = zeros(301,1);
Wd1   = zeros(301,1);
Stp1 = zeros(301,1);
Ri1  = zeros(301,1);
Spw1 = zeros(301,1);
Ai1  = zeros(301,1);
Maxrel1 = zeros(301,1);
Minrel1 = zeros(301,1);
Est1 = zeros(301,1);
Est0 = zeros(301,1);
Rt1 = zeros(301,1);
```

```
% Initial value of storage at May 1979
Stp1(1) = 4244.7;
Ai1(1) = 161.46;
Ess(1) = 4142.53;

% hva1 is the height-volume-area curve for Sirikit dam
% Vol1 is volume of Sirikit dam
% Lev1 is water level of Sirikit dam
% Area1 is area of Sirikit dam
% Voldiff1 is different between the volume interval
% Levdiff1 is different between the water level interval
% Areadiff1 is different between the area interval


hdata = load('hva1.txt','%f');

Vol1      = hdata(:,1);
Lev1      = hdata(:,2);
Area1     = hdata(:,3);
Voldiff1  = hdata(:,4);
Levdiff1  = hdata(:,5);
Areadiff1 = hdata(:,6);
hva1 = [Vol1,Lev1,Area1,Voldiff1,Levdiff1,Areadiff1];

cdata = load('area.txt','%f');
Gr    = cdata(:,1);
Area2 = cdata(:,2);
area  = [Gr,Area2];
```

```
i = 2;
for ii = 1 : 300
    if Stp1(ii)>= 2850
       Est1(ii) = Stp1(ii) - 2850;
    elseif Stp1(ii)< 2850
       Est1(ii) = 2850 - Stp1(ii);
    end

    % Determine Type for release funtion and cultivated area (for initial
    % condition)
    if M2(ii) == 0 && Ess(1) <= 2033
          Type21(ii) = 5;
    elseif M2(ii) == 0 && Ess(1) > 2033 && Ess(1) <= 3826
          Type21(ii) = 6;
    elseif M2(ii) == 0 && Ess(1) > 3826 && Ess(1) <= 5767
          Type21(ii) = 7;
    elseif M2(ii) == 0 && Ess(1) > 5767
          Type21(ii) = 8;
    end
    % Determine Sub Type for cultivated area
    % Determine the cultivated area for dry season (for initial
    % condition)
    if M2(ii) == 0 && Type21(ii) == 5 && Ess(1) > 2008
       Type22(ii) = 51;
       Ag(ii) = vlookup(Type22(ii),area,2);
       Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
       Wd1(ii) = Wd1(ii)/1000;
    elseif M2(ii) == 0 && Type21(ii) == 5 && Ess(1) > 1916 && Ess(1) <= 2008
```

```
    Type22(ii) = 52;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 0 && Type21(ii) == 5 && Ess(1) <= 1916
    Type22(ii) = 53;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 0 && Type21(ii) == 6 && Ess(1) > 3173
    Type22(ii) = 61;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 0 && Type21(ii) == 6 && Ess(1) > 2512 && Ess(1)<= 3173
    Type22(ii) = 62;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 0 && Type21(ii) == 6 && Ess(1) <= 2512
    Type22(ii) = 63;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 0 && Type21(ii) == 7 && Ess(1) > 5328
    Type22(ii) = 71;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
```

```
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 0 && Type21(ii) == 7 && Ess(1) > 4753 && Ess(1) <= 5328
    Type22(ii) = 72;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 0 && Type21(ii) == 7 && Ess(1) <= 4753
    Type22(ii) = 73;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 0 && Type21(ii) == 8 && Ess(1) > 6590
    Type22(ii) = 81;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 0 && Type21(ii) == 8 && Ess(1) > 6477 && Ess(1) <= 6590
    Type22(ii) = 82;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 0 && Type21(ii) == 8 && Ess(1) <= 6477
    Type22(ii) = 83;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
end
```

```
if and(M2(ii) == 1,Est1(i-1) <= 648)
   Type21(ii) = 1;
elseif M2(ii) == 1 && Est1(i-1) > 648 && Est1(i-1) <= 1381
   Type21(ii) = 2;
elseif M2(ii) == 1 && Est1(i-1) > 1381 && Est1(i-1) <= 2991
   Type21(ii) = 3;
elseif M2(ii) == 1 && Est1(i-1) > 2991
   Type21(ii) = 4;
end

% Determine Sub Type for cultivated area
% Determine the cultivated area for wet season
if M2(ii) == 1 && Type21(ii) == 1 && Est1(i-1) > 480
   Type22(ii) = 11;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
   Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 1 && Type21(ii) == 1 && Est1(i-1) > 246 && Est1(i-1) <= 480
   Type22(ii) = 12;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
   Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 1 && Type21(ii) == 1 && Est1(i-1) <= 246
   Type22(ii) = 13;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
   Wd1(ii) = Wd1(ii)/1000;
end
```

```
if M2(ii) == 1 && Type21(ii) == 2 && Est1(i-1) > 1042
   Type22(ii) = 21;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
   Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 1 && Type21(ii) == 2 && Est1(i-1) > 737 && Est1(i-1) <= 1042
   Type22(ii) = 22;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
   Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 1 && Type21(ii) == 2 && Est1(i-1) <= 737
   Type22(ii) = 23;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
   Wd1(ii) = Wd1(ii)/1000;
end
if M2(ii) == 1 && Type21(ii) == 3 && Est1(i-1) > 2483
   Type22(ii) = 31;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
   Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 1 && Type21(ii) == 3 && Est1(i-1) > 1955 && Est1(i-1) <= 2483
   Type22(ii) = 32;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
   Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 1 && Type21(ii) == 3 && Est1(i-1) <= 1955
   Type22(ii) = 33;
```

```
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
   Wd1(ii) = Wd1(ii)/1000;
end
if M2(ii) == 1 && Type21(ii) == 4 && Est1(i-1) > 3609
   Type22(ii) = 41;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
   Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 1 && Type21(ii) == 4 && Est1(i-1) > 3107 && Est1(i-1) <= 3609
   Type22(ii) = 42;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
   Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 1 && Type21(ii) == 4 && Est1(i-1) <= 3107
   Type22(ii) = 43;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
   Wd1(ii) = Wd1(ii)/1000;
end
% Determine the cultivated area for wet season
if M2(ii) >= 2 && M2(ii) <= 6 && Type22(ii-1) == 11
   Type22(ii) = 11;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
   Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) >= 2 && M2(ii) <= 6 && Type22(ii-1) == 12
   Type22(ii) = 12;
```

```
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) >= 2 && M2(ii) <= 6 && Type22(ii-1) == 13
    Type22(ii) = 13;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) >= 2 && M2(ii) <= 6 && Type22(ii-1) == 21
    Type22(ii) = 21;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) >= 2 && M2(ii) <= 6 && Type22(ii-1) == 22
    Type22(ii) = 22;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) >= 2 && M2(ii) <= 6 && Type22(ii-1) == 23
    Type22(ii) = 23;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) >= 2 && M2(ii) <= 6 && Type22(ii-1) == 31
    Type22(ii) = 31;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
    Wd1(ii) = Wd1(ii)/1000;
```

```
elseif M2(ii) >= 2 && M2(ii) <= 6 && Type22(ii-1) == 32
   Type22(ii) = 32;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
   Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) >= 2 && M2(ii) <= 6 && Type22(ii-1) == 33
   Type22(ii) = 33;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
   Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) >= 2 && M2(ii) <= 6 && Type22(ii-1) == 41
   Type22(ii) = 41;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
   Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) >= 2 && M2(ii) <= 6 && Type22(ii-1) == 42
   Type22(ii) = 42;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
   Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) >= 2 && M2(ii) <= 6 && Type22(ii-1) == 43
   Type22(ii) = 43;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*29479;
   Wd1(ii) = Wd1(ii)/1000;
end

% Determine Type for release funtion and cultivated area
```

```
if     M2(ii) == 7 && Est1(i-1) <= 2033
       Type21(ii) = 5;
elseif M2(ii) == 7 && Est1(i-1) > 2033 && Est1(i-1) <= 3826
       Type21(ii) = 6;
elseif M2(ii) == 7 && Est1(i-1) > 3826 && Est1(i-1) <= 5767
       Type21(ii) = 7;
elseif M2(ii) == 7 && Est1(i-1) > 5767
       Type21(ii) = 8;
end
% Determine Sub Type for cultivated area
% Determine the cultivated area for dry season
if M2(ii) == 7 && Type21(ii) == 5 && Est1(i-1) > 2008
   Type22(ii) = 51;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
   Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 7 && Type21(ii) == 5 && Est1(i-1) > 1916 && Est1(i-1) <= 2008
   Type22(ii) = 52;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
   Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 7 && Type21(ii) == 5 && Est1(i-1) <= 1916
   Type22(ii) = 53;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
   Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 7 && Type21(ii) == 6 && Est1(i-1) > 3173
   Type22(ii) = 61;
```

```
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 7 && Type21(ii) == 6 && Est1(i-1) > 2512 && Est1(i-1) <= 3173
    Type22(ii) = 62;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 7 && Type21(ii) == 6 && Est1(i-1) <= 2512
    Type22(ii) = 63;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 7 && Type21(ii) == 7 && Est1(i-1) > 5328
    Type22(ii) = 71;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 7 && Type21(ii) == 7 && Est1(i-1) > 4753 && Est1(i-1) <= 5328
    Type22(ii) = 72;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 7 && Type21(ii) == 7 && Est1(i-1) <= 4753
    Type22(ii) = 73;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
```

```
elseif M2(ii) == 7 && Type21(ii) == 8 && Est1(i-1) > 6590
   Type22(ii) = 81;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
   Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 7 && Type21(ii) == 8 && Est1(i-1) > 6477 && Est1(i-1) <= 6590
   Type22(ii) = 82;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
   Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) == 7 && Type21(ii) == 8 && Est1(i-1) <= 6477
   Type22(ii) = 83;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
   Wd1(ii) = Wd1(ii)/1000;
end

% Determine Sub Type for cultivated area
% Determine the cultivated area for dry season

if M2(ii) > 7 && M2(ii) <= 12 && Type22(ii-1) == 51
   Type22(ii) = 51;
   Ag(ii) = vlookup(Type22(ii),area,2);
   Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
   Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) > 7 && M2(ii) <= 12 && Type22(ii-1) == 52
   Type22(ii) = 52;
   Ag(ii) = vlookup(Type22(ii),area,2);
```

```
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) > 7 && M2(ii) <= 12 && Type22(ii-1) == 53
    Type22(ii) = 53;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) > 7 && M2(ii) <= 12 && Type22(ii-1) == 61
    Type22(ii) = 61;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) > 7 && M2(ii) <= 12 && Type22(ii-1) == 62
    Type22(ii) = 62;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) > 7 && M2(ii) <= 12 && Type22(ii-1) == 63
    Type22(ii) = 63;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) > 7 && M2(ii) <= 12 && Type22(ii-1) == 71
    Type22(ii) = 71;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) > 7 && M2(ii) <= 12 && Type22(ii-1) == 72
```

```
    Type22(ii) = 72;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) > 7 && M2(ii) <= 12 && Type22(ii-1) == 73
    Type22(ii) = 73;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) > 7 && M2(ii) <= 12 && Type22(ii-1) == 81
    Type22(ii) = 81;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) > 7 && M2(ii) <= 12 && Type22(ii-1) == 82
    Type22(ii) = 82;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
elseif M2(ii) > 7 && M2(ii) <= 12 && Type22(ii-1) == 83
    Type22(ii) = 83;
    Ag(ii) = vlookup(Type22(ii),area,2);
    Wd1(ii) = Wu1(ii)*Ag(ii) + Wu2(ii)*31087;
    Wd1(ii) = Wd1(ii)/1000;
end


%Determine release function in each water season
```

```
if and(M1(ii) == 1,Est1(ii) < 648)
   fismat = readfis('Verydry_wet');
   Type1(ii)   = 1;
   Ri1(ii) = evalfis([Est1(ii) Inf1(ii) Sfo1(ii) Rf21(ii) Wd1(ii)],fismat);
elseif M1(ii) == 1 && Est1(ii) > 648 && Est1(ii) <= 1381
   fismat = readfis('Dry_wet');
   Type1(ii) = 2;
   Ri1(ii) = evalfis([Est1(ii) Inf1(ii) Sfo1(ii) Rf21(ii) Wd1(ii)],fismat);
elseif M1(ii) == 1 && Est1(ii) > 1381 && Est1(ii) <= 2991
   fismat = readfis('Normal_wet');
   Type1(ii) = 3;
   Ri1(ii) = evalfis([Est1(ii) Inf1(ii) Sfo1(ii) Rf21(ii) Wd1(ii)],fismat);
elseif M1(ii) == 1 && Est1(ii) > 2991
   fismat = readfis('High_wet');
   Type1(ii) = 4;
   Ri1(ii) = evalfis([Est1(ii) Inf1(ii) Sfo1(ii) Rf21(ii) Wd1(ii)],fismat);
end

if M1(ii) >= 2 && M1(ii) <= 6 && Type1(ii-1) == 1
   fismat = readfis('Verydry_wet');
   Type1(ii) = 1;
   Ri1(ii) = evalfis([Est1(ii) Inf1(ii) Sfo1(ii) Rf21(ii) Wd1(ii)],fismat);
elseif M1(ii) >= 2 && M1(ii) <= 6 && Type1(ii-1) == 2
   fismat = readfis('Dry_wet');
   Type1(ii) = 2;
   Ri1(ii) = evalfis([Est1(ii) Inf1(ii) Sfo1(ii) Rf21(ii) Wd1(ii)],fismat);
elseif M1(ii) >= 2 && M1(ii) <= 6 && Type1(ii-1) == 3
   fismat = readfis('Normal_wet');
```

```
   Type1(ii) = 3;
   Ri1(ii) = evalfis([Est1(ii) Inf1(ii) Sfo1(ii) Rf21(ii) Wd1(ii)],fismat);
elseif M1(ii) >= 2 && M1(ii) <= 6 && Type1(ii-1) == 4
   fismat = readfis('High_wet');
   Type1(ii) = 4;
   Ri1(ii) = evalfis([Est1(ii) Inf1(ii) Sfo1(ii) Rf21(ii) Wd1(ii)],fismat);
end
if M1(ii) == 7 && Est1(ii) <= 2033
      fismat = readfis('Verydry_dry');
      Type1(ii) = 5;
      Ri1(ii) = evalfis([Est1(ii) Inf1(ii) Sfo1(ii) Rf21(ii) Wd1(ii)],fismat);
elseif M1(ii) == 7 && Est1(ii) > 2033 && Est1(ii) <= 3826
      fismat = readfis('Dry_dry');
      Type1(ii) = 6;
      Ri1(ii) = evalfis([Est1(ii) Inf1(ii) Sfo1(ii) Rf21(ii) Wd1(ii)],fismat);
elseif M1(ii) == 7 && Est1(ii) > 3826 && Est1(ii) <= 5767
      fismat = readfis('Normal_dry');
      Type1(ii) = 7;
      Ri1(ii) = evalfis([Est1(ii) Inf1(ii) Sfo1(ii) Rf21(ii) Wd1(ii)],fismat);
elseif M1(ii) == 7 && Est1(ii) > 5767
      fismat = readfis('High_dry');
      Type1(ii) = 8;
      Ri1(ii) = evalfis([Est1(ii) Inf1(ii) Sfo1(ii) Rf21(ii) Wd1(ii)],fismat);
end
if M1(ii) > 7 && M1(ii) <= 12 && Type1(ii-1) == 5
      fismat = readfis('Verydry_dry');
      Type1(ii) = 5;
      Ri1(ii) = evalfis([Est1(ii) Inf1(ii) Sfo1(ii) Rf21(ii) Wd1(ii)],fismat);
```

```
elseif M1(ii) > 7 && M1(ii) <= 12 && Type1(ii-1) == 6
      fismat = readfis('Dry_dry');
      Type1(ii) = 6;
      Ri1(ii) = evalfis([Est1(ii) Inf1(ii) Sfo1(ii) Rf21(ii) Wd1(ii)],fismat);
elseif M1(ii) > 7 && M1(ii) <= 12 && Type1(ii-1) == 7
      fismat = readfis('Normal_dry');
      Type1(ii) = 7;
      Ri1(ii) = evalfis([Est1(ii) Inf1(ii) Sfo1(ii) Rf21(ii) Wd1(ii)],fismat);
elseif M1(ii) > 7 && M1(ii) <= 12 && Type1(ii-1) == 8
      fismat = readfis('High_dry');
      Type1(ii) = 8;
      Ri1(ii) = evalfis([Est1(ii) Inf1(ii) Sfo1(ii) Rf21(ii) Wd1(ii)],fismat);
end
if Type1(ii) == 1
   Maxrel1(ii) = 735.7;
   Minrel1(ii) = 11.4;
elseif Type1(ii) == 2
   Maxrel1(ii) = 1830.5;
   Minrel1(ii) = 42;
elseif Type1(ii) == 3
   Maxrel1(ii) = 1061.7;
   Minrel1(ii) = 64.3;
elseif Type1(ii) == 4
   Maxrel1(ii) = 1280.5;
   Minrel1(ii) = 42.9;
elseif Type1(ii) == 5
   Maxrel1(ii) = 655.5;
   Minrel1(ii) = 45.6;
```

```
elseif Type1(ii) == 6
   Maxrel1(ii) = 997.3;
   Minrel1(ii) = 47.6;
elseif Type1(ii) == 7
   Maxrel1(ii) = 1006.4;
   Minrel1(ii) = 40.5;
elseif Type1(ii) == 8
   Maxrel1(ii) = 1384.9;
   Minrel1(ii) = 186.8;
end
 %check maximum release
 if Ri1(ii) > Maxrel1(ii)
  Ri1(ii) = Maxrel1(ii);
 elseif and(Ri1(ii) <= Maxrel1(ii),Ri1(ii) > Minrel1(ii))
  Ri1(ii) = Ri1(ii);
 elseif Ri1(ii) <= Minrel1(ii);
  Ri1(ii) = Minrel1(ii);
end
  Rf11(ii) = 0.25*Rf11(ii)*Ai1(ii)/1000;
  Ei1(ii)  = 0.78*Ei1(ii)*Ai1(ii)/1000;
  Stp1(ii+1) = Stp1(ii) + Inf1(ii) + Rf11(ii) - Ei1(ii) - Ri1(ii);
  Ai1(ii+1)  = (Stp1(ii+1) - vlookup(Stp1(ii+1),hva1,1))*vlookup(Stp1(ii+...
      1),hva1,6)/vlookup(Stp1(ii+1),hva1,4)+vlookup(Stp1(ii+1),hva1,3);
 %check water release for the flood control

 if  Stp1(ii+1) >= 9485
  Spw1(ii) = Stp1(ii+1) - 9485;
  Stp1(ii+1) = Stp1(ii+1) - Spw1(ii);
```

```
    end
    Rt1(i-1) = Spw1(ii) + Ri1(ii);
    i = i+1;
end

    CalALL  = [Stp1 Est1 Type1 Type22 Ag Wd1 Ri1 Maxrel1 Minrel1 Spw1 Rt1];
save Result_SK.txt -ascii -tabs CalALL
```

VITA

Name Mr. Winai Chaowiwat

Birth date 11 December 1973

Education

1995 Graduate Bachelor Degree of Civil Engineering, Department of Civil Engineering, Faculty of Engineering Rangsit University

1998 Graduate Master Degree of Civil Engineering, Department of Water Resources Engineering, Faculty of Engineering Chulalongkorn University

Training

Meteorological Research Institute (MRI)

- Capacity Development for Adaptation to Climate Change in Asia Climate Change Analysis

United Nation University (UNU-ISP Institute for Sustainable and Peace)

1) Downscaling Weather Forecasts

2) Geographic Information Systems

3) Building Resilience to Climate Change

Experience

1) Water resource engineer at Progress Technology Consultant

2) Water resource engineer at Sigma Hydro Consultant

3) Water resource engineer at Water Resources Management Research Unit Laboratory, ChulalongkornUniversity

Publications

Chaowiwat, W. and Likitdecharote, K. Effect of Climate Change on Potential Evapotranspiration Case Study : Lower Chaopraya Basin, The 1st NPRU Academic Conference, October 23-24, 2008, Nakhon Pathom, Thailand.

Kitoh, A., Kusunoki,S., Sato, Y., Ferdousi, N., Rahman, M., Makmur E.E.S., Liza Solmoro Solis, A., Chaowiwat, W. and Tran Dinh Trong, Chapter 2.1 Climate Change Projections in Some Asian Countries in book Climate Change Adaptation and

International Development Making Development Cooperation More Effective, JICA Research Institute, 2010.

Chaowiwat, W., and Koontanakulvong, S. Climate change impact on water resource management in East Coast Basin Thailand, Proc. 2nd Regional Conference on Global Environment, Ho Chi Minh City, Vietnam March 8-9th , 2010.

Koontanakulvong, S.,Chaowiwat, W. Corrected MRI GCM data for Thailand, Technical Report , Chulalongkorn University, December, 2010.

Koontanakulvong S., Chaowiwat W. GCM Data Comparison and its application to water disaster adaptation measures in Thailand. Technical Report, Chulalongkorn University, March, 2011.

Chaowiwat, W., Hydrology Impact Assessment of Climate Change to Nan River Basin, The Conference 2nd Water Management, Department of Water Resources, 26-27 July 2012, Bangkok, Thailand. (in Thai)

Chaowiwat, W., and Koontanakulvong, S. Statistical Forecasting of Rainfall with ENSO index in the Chao Phraya River Basin in Thailand, PAWEES 2012 International Conference, Challenges of Water & Environmental Management in Monsoon Asia, 27-29 November 2012, Thailand.

Koontanakulvong S., Chaowiwat W. Climate Change Impact on Irrigation System and Farmers' response, Paddy Water Environ., July, 2013.